PERSPECTIVE

Used planet: A global history

Erle C. Ellis[a,1], Jed O. Kaplan[b], Dorian Q. Fuller[c], Steve Vavrus[d], Kees Klein Goldewijk[e], and Peter H. Verburg[f]

[a]Department of Geography and Environmental Systems, University of Maryland, Baltimore County, Baltimore, MD 21250; [b]ARVE Group, Environmental Engineering Institute, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland; [c]Institute of Archaeology, University College London, London WC1H 0PY, United Kingdom; [d]Center for Climatic Research, Gaylord Nelson Institute for Environmental Studies, University of Wisconsin, Madison, WI 53706; [e]Netherlands Environmental Assessment Agency (PBL), 3720 AH Bilthoven and Utrecht University (UU), 3584 CS, Utrecht, The Netherlands; and [f]Institute for Environmental Studies, Amsterdam Global Change Institute, VU University Amsterdam, 1081 HV, Amsterdam, The Netherlands

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Human use of land has transformed ecosystem pattern and process across most of the terrestrial biosphere, a global change often described as historically recent and potentially catastrophic for both humanity and the biosphere. Interdisciplinary paleoecological, archaeological, and historical studies challenge this view, indicating that land use has been extensive and sustained for millennia in some regions and that recent trends may represent as much a recovery as an acceleration. Here we synthesize recent scientific evidence and theory on the emergence, history, and future of land use as a process transforming the Earth System and use this to explain why relatively small human populations likely caused widespread and profound ecological changes more than 3,000 y ago, whereas the largest and wealthiest human populations in history are using less arable land per person every decade. Contrasting two spatially explicit global reconstructions of land-use history shows that reconstructions incorporating adaptive changes in land-use systems over time, including land-use intensification, offer a more spatially detailed and plausible assessment of our planet's history, with a biosphere and perhaps even climate long ago affected by humans. Although land-use processes are now shifting rapidly from historical patterns in both type and scale, integrative global land-use models that incorporate dynamic adaptations in human–environment relationships help to advance our understanding of both past and future land-use changes, including their sustainability and potential global effects.

Anthropocene | environmental history | holocene | niche construction | agriculture

Human populations and their use of land have now transformed ecosystem pattern and process across most of the terrestrial biosphere (1, 2), causing major global changes in biodiversity (3), biogeochemistry (4–6), geomorphic processes (7), and climate (8). Together with other anthropogenic changes in the Earth system that may herald the emergence of a new geological epoch, the Anthropocene (9, 10), the global changes caused by human use of land are generally portrayed as the result of an unchecked and accelerating process that is mostly recent in origin (11) and therefore presents an impending catastrophe for humanity, the biosphere, and the Earth system in general (3, 12). This article investigates this hypothesis by assessing whether global changes caused by human use of land are mostly recent and result from processes that are now accelerating.

Broad evidence from archaeology, paleoecology, environmental history, and other disciplines suggests that direct human alteration of terrestrial ecosystems by hunting, foraging, land clearing, agriculture, and other activities has been profound in some regions at least since the late Pleistocene, with long-term impacts from forest clearing, increased fire frequencies, megafaunal extinctions, species invasions, soil erosion, and others (13, 14). Despite widespread recognition that hunter-gatherers and early farmers were capable of transforming terrestrial ecosystems around the world, these early anthropogenic changes have yet to be understood as global change processes and are generally portrayed by global change scientists as localized and insignificant compared with contemporary changes in the Earth system (11, 14).

Global change science has focused on the emergence of industrial processes over the past three centuries as the critical period within which anthropogenic global change processes, including land use, became significant forces driving global changes in the Earth System (14–18). As a result of this emphasis and the prior absence of adequate tools, theory, and data, quantitative global land-use histories for earlier periods of the Holocene have only recently been developed (4, 19–21). Although these new global land-use histories remain at an early stage of development, their quantitative and spatially detailed global predictions offer an unprecedented opportunity to investigate the global extent, timing, driving forces, and impacts of land use as a process transforming the Earth System over the Holocene.

Even as human populations increase beyond seven billion and per capita demand for food is increasing, rates of growth in the global extent and per capita use of land for agriculture seem to be declining (22). This has been made possible by agricultural intensification, the adoption of technologies enabling dramatic increases in food production from a given area of agricultural land (23). Processes of land-use intensification, if viewed more broadly as adaptive processes by which human populations systematically adopt increasingly productive land-use technologies, have major implications for understanding the dynamics of land use and its potential impacts over the Holocene (24), as will be shown by examining the spatially explicit predictions of two different global models of land-use history.

Quantitative Global Modeling of Land-Use History

The first spatially explicit global land-use reconstructions date to the 1980s (25, 26), with land-use histories covering the past three centuries emerging in the late 1990s (27, 28). However, the first global land-use histories spanning the last millennium (20, 21) and the majority of the Holocene (4, 19) have been published only in the past few

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[1]To whom correspondence should be addressed. E-mail: ece@umbc.edu.

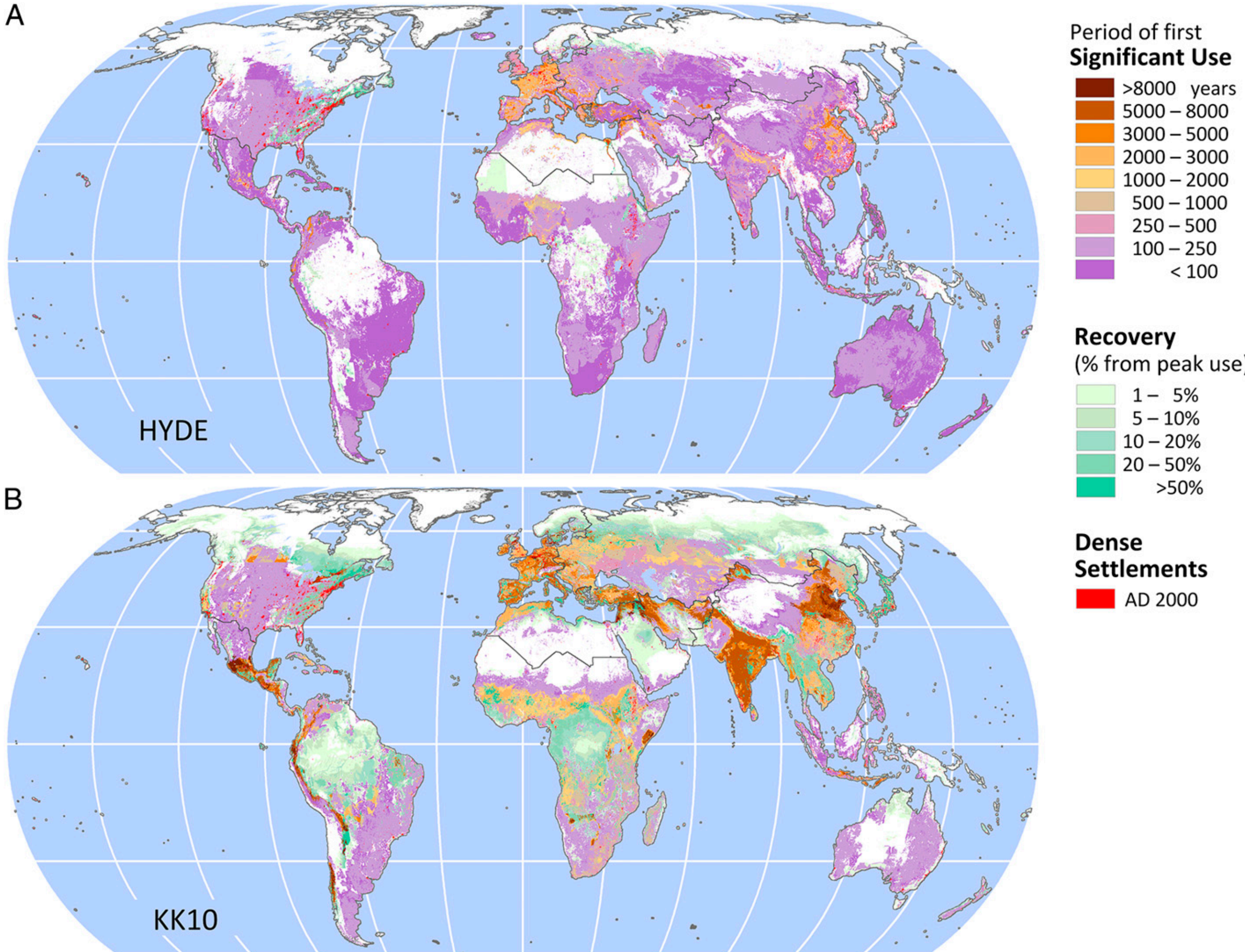

Fig. 1. Time period of first significant land use and recovery from peak land use, 6000 B.C. to A.D. 2000, based on historical reconstructions from the HYDE (*A*) and KK10 (*B*) models. Dense settlements from ref. 1; black lines delimit regions in Fig. 2. Eckert IV projection.

years. Data and methods for land-use history reconstructions differ significantly for three different time periods within the Holocene. For the contemporary period, 1970s to present, remote sensing observations and statistical data provide strong empirical support. For the "historical period," roughly 1700 to present in most regions, statistical data for land use and population are available with differing accuracy and coverage in different regions at different times. In the "prehistorical period" (before 1700, depending on region), all land-use estimates depend on model-based reconstructions from limited sets of empirical data.

Historical land-use reconstructions share standard core procedures. Global maps for recent time periods are prepared by integrating satellite and census data for land use at national and subnational levels, with satellite data providing a means to disaggregate the administrative-level data (27, 29). Recent geographic patterns are then forecasted into the past (hindcasted) using algorithms designed to maintain consistency with historical administrative-level data (27, 28, 30). Although showing some significant differences, global land-use reconstructions for the past 300 y tend toward similar regional and global trends (31).

Spatially explicit global land-use reconstructions for prehistorical time periods use models to allocate land use to spatially explicit global datasets for human populations over time. Global population datasets are derived from compilations of subglobal population estimates, regional population reconstructions, and available spot estimates (32). Prehistorical land use is then predicted from global population datasets by one of two existing methods. The first and simplest has been to extrapolate contemporary patterns of land-use per capita into the past (31). The alternative has been to use empirically derived relationships between land-use per capita and population density over time (4, 20, 33).

Tale of Two Models: The Importance of Land-Use Intensification in Global Land Change History

Comparing spatially explicit land-use predictions from the two main global models of land use across the Holocene reveals the potentially pivotal role of land-use intensification as a global change process (Figs. 1 and 2). HYDE, the first and most popular model (Figs. 1*A* and 2 *A* and *C*) (31), effectively omits land-use intensification by assuming that land-use per capita remained approximately constant over time, closely resembling the pattern in A.D. 1961, the first year for which global Food and Agriculture Organization of the United Nations statistics

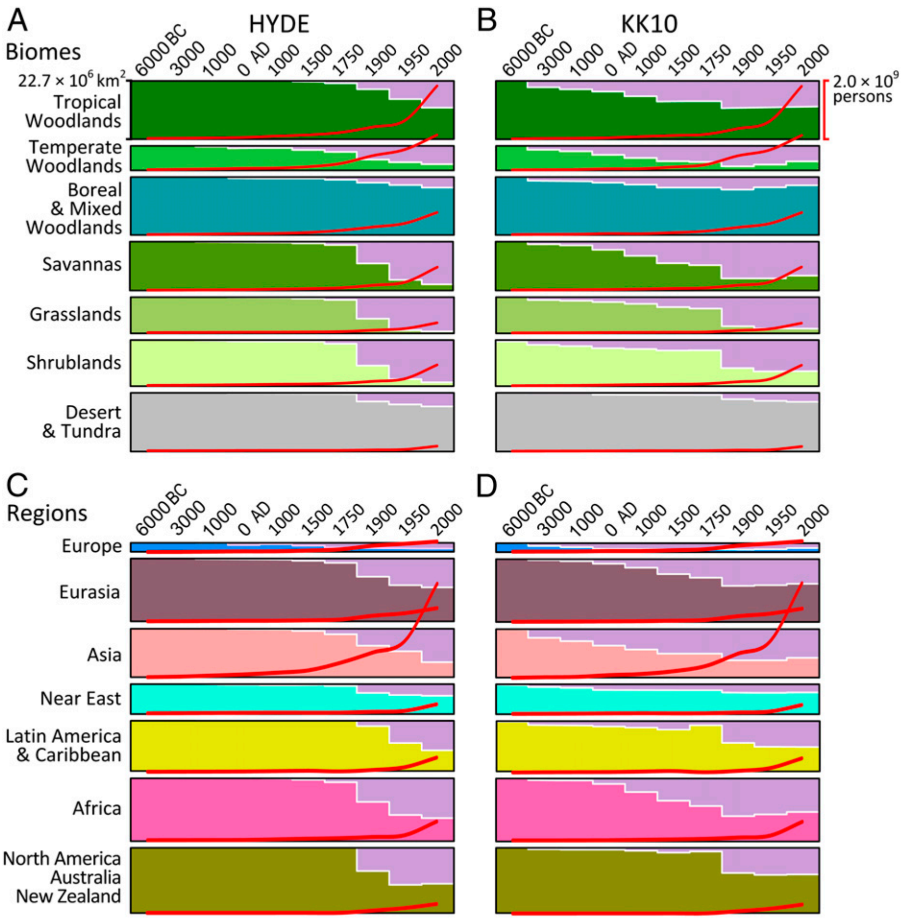

Fig. 2. Global areas of significant land use (purple) and total population (red line) within biomes (*A* and *B*) and world regions (*C* and *D*), 6000 B.C. to A.D. 2000, based on the HYDE (*A* and *C*) and KK10 (*B* and *D*) historical land-use reconstructions.

are available. The KK10 model (Figs. 1*B* and 2 *B* and *D*) (4) predicts land use from population data using empirically derived nonlinear relationships with population density. In this model, low-density populations with high per-capita land use first expand to fill all usable land and then intensify land use (use less land per capita) as population densities increase over time. The strikingly different predictions of these two models (Figs. 1 and 2) are almost entirely the result of differences in the way they represent land-use intensification processes; their population datasets are nearly the same (Fig. 2).

HYDE predicts that except for the developed regions of Europe, human use of land was insignificant in every biome and region before A.D. 1750 (Fig. 2 *A* and *C*). In KK10, land use emerges as a major global change far earlier in the Holocene, with more than 20% of Earth's Temperate Woodlands already significantly used by 1000 B.C. and most other biomes by A.D. 1000 (Fig. 2*B*). Regionally, KK10 predicts that 20% of Europe and Asia were already used significantly by 3000 B.C. and most other regions by A.D. 1000 (Fig. 2*D*); HYDE suggests that no region outside Europe reached these levels before A.D. 1900. KK10 also indicates that large areas of Earth's land may now be recovering from higher levels of land use in earlier periods (Fig. 1). Overall, these global model intercomparisons reveal two very different Earth histories, one in which land use has recently accelerated, and one in which land use began early and became strikingly more efficient over time, leading to recoveries in some regions.

No single existing model of Holocene land use is able to make entirely accurate global predictions, and there are significant differences in the land-use definitions of different models, with HYDE focusing exclusively on cultivated, pasture, and urban areas, and KK10 on land use more generally, including shifting cultivation and forest harvest along with agricultural land use. Nevertheless, with these caveats in mind, it is important to know which model's predictions come closer to the evidence that we now have and to learn what the differences between models can tell us about the general importance of land use and its intensification as global change processes across the Holocene.

Land-Use Intensification Theory

Given the important role that different assumptions relating to per capita land-use dynamics can play in understanding land-use change over the Holocene, theoretical work on land-use intensification is relevant. Agricultural intensification theory was first formulated by Ester Boserup to explain higher levels of agricultural productivity associated with higher population densities in traditional smallholder agriculture (34, 35). Boserup's theory opposed the classic Malthusian claim that human populations were limited by agricultural productivity (36), proposing instead that agriculturalists increased productivity only when population increases demanded this, because their objective was to invest the least amount of labor, technology, and other resources necessary to support their livelihoods, even when the technological capacity for greater productivity was available (34, 37). Although rarely applied now in its original form, Boserup's theory inspired a wide array of intensification theories across archaeology (14), anthropology (38), geography (39), development studies (40), economics, environmental history, and other disciplines and has been extended to include land tenure and other social institutions, market forces, and nonagricultural populations (39, 41, 42).

For this assessment, we define land-use intensification broadly as the adaptive response of human populations to demographic, social, and economic pressures leading to the adoption of increasingly productive land-use systems. Although this process tends to result

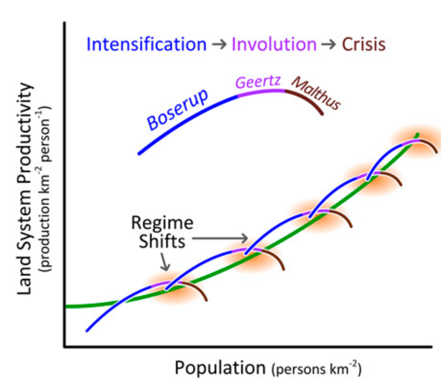

Fig. 3. General model of land-use intensification. Arcs depict individual land-use systems with three phases: intensification (Boserup; 34), involution (Geertz; 43), and crisis (Malthus; 36), with regime shifts from less to more productive land systems. Green line highlights general trend toward increasing productivity with population.

in a general increasing trend in land productivity with population density, the relationship between any given population and the productivity of its land-use systems is dynamic and responsive not only to demographic forcing but also to the social and economic processes regulating resource demand, land availability, technology adoption and availability, environmental variation, and the potential for intensive use of land to degrade its potential productivity over time (14, 39, 41). As a result, a general trend toward increasing productivity with population density is attained not as a smooth and continuous process but through a complex succession of land system regime shifts, some of them regressive, with populations and their production systems subject to both surplus production and productivity crises, as depicted in Fig. 3.

In this general model of intensification, land-use systems tend to follow a three-phase relationship between productivity and population (Fig. 3). In the "intensification" phase, adoption of more productive technologies enables productivity to increase faster than population. "Involution" occurs once technology-driven productivity increases are exhausted, such that only net increases in labor or other costly inputs enable increases in production (43). Finally, production "crises" result once all capacity to enhance land productivity is exhausted and food production cannot keep up with increasing populations (36). By this model, hunter-gatherer's use of fire to enhance foraging success is a form of land-use intensification, as is land clearing for shifting cultivation, wet rice cultivation, the moldboard plow, and contemporary use of synthetic nitrogen fertilizer and mechanization (44, 45). In all cases, regime shifts in land system productivity are driven not by technological innovations in themselves but rather by demographic or social demands for surplus production or reduced labor inputs, usually well after the requisite technologies have become widely available (45). On the basis of this general model of land-use intensification as a global change process, its prevalence and global importance in different time periods across the Holocene may be assessed according to archeological, historical, and contemporary evidence.

Land-Use Intensification in the Late Pleistocene and Early Holocene

An increasing number of archaeological studies demonstrate that human hunter-gatherers modify environments for their own benefit by processes consistent with our general model of land-use intensification (14). As humans dispersed from Africa to other continents, microcharcoal records attest to new fire regimes and heightened levels of biomass burning associated with their arrival (46, 47). Hunter-gatherers are known to set fires intentionally to create and maintain early successional ecosystems, which generally have higher productivity than undisturbed ecosystems, in efforts to boost the local availability of food plants and game animals (47, 48). Studies have suggested that intentional burning could have had very large effects on vegetation cover in the mesic environments of New Zealand (49), the wet tropical forests of the pre-Columbian Amazon (50), and across the savannas and woodlands of Africa (51). However, the role of fire in preagricultural land-use change remains highly controversial. Most continental to global reviews of the Holocene sedimentary charcoal record have concluded that fire activity is most strongly correlated with climate variability and suggest that anthropogenic burning had only local effects on land cover (52, 53). Even in Australasia, where aboriginal use of fire is perhaps best documented (54), the long-term influence of humans on fire has proved difficult to separate from climate variability (55). Human use of fire therefore remains a potentially massive global change that cannot yet be ruled out or in (56).

Once settled into new environments, human populations grew to levels unprecedented by earlier Hominins, putting pressure on plant and animal resources that ultimately led to expanding human procurement of increasingly smaller and harder to catch prey, in an adaptive transition that archaeologists have dubbed the "broad spectrum revolution" (57). Increasingly intensive use of animal resources is well demonstrated across both Eurasia and Africa at the end of the Pleistocene by progressive declines in larger-bodied game and growing use of smaller bodied game, often ending in regional extinctions and associated major ecosystem shifts (3, 58). Processing techniques such as grinding, boiling, fermenting, and roasting were gradually adopted to enhance nutrient bioavailability from plant and animal foods, further increasing the amount of food extractable from a given area of land (59). These techniques may have boosted the nutritional returns on foraging efforts for small seeds and tubers to levels that made them worth exploiting at high levels for the first time (59), thereby potentially setting them on course to later domestication (60). By the late Pleistocene, hunter-gatherers had also developed another essential preadaptation to agriculture: the planting of seeds. Recent genetic and archaeobotanical evidence indicates that Pleistocene humans were cultivating and translocating bottlegourds (*Lagenaria sciceraria*) from their wild source in Africa, through Asia, and to the Americas by 7000 B.C., suggesting that Asians brought seeds and seed propagation and processing technologies with them when peopling the Americas (60). These early technologies enabled increasing exploitation of and reliance on species that were to become crops, putting humanity on the road to agriculture.

Adaptive Intensification in the Early Holocene

Although diverse across regions and time periods, most human populations likely entered the Holocene living within cultures that had become technologically adapted to denser populations by pre- and protoagricultural processes of land-use intensification, including dietary broadening, the use of fire to enhance foraging success, food processing, the propagation of useful species, and other accumulated products of social learning (61, 62), together with the increasingly cooperative exchange of these technologies and their material products (38). Although preagricultural technologies for ecosystem engineering have far lower productivities than the agricultural technologies that came later, they still enabled human populations to grow beyond the capabilities of unaltered ecosystems to support them. As populations gradually increased, more intensive land-use practices were adopted to sustain them (intensification), or populations migrated to areas with lower levels of land use (extensification), including uninhabited wildlands. By the early Holocene, hunter-gatherer populations had spread across the Earth and depended on early land-use intensification processes to survive and to grow and lived mostly within ecosystems reshaped by their ancestors to enhance their productivity. The stage was set for the rise of agriculture.

Emergence and Expansion of Agriculture

Agricultural systems emerged across most continents by early to mid-Holocene by a variety of different pathways in as many as 24 plausibly independent centers of early domestication, with later spread to adjacent regions (60, 63). Some developed at the Pleistocene–Holocene transition, including Southwest Asia (60, 64), South America (65, 66), and North China (67), whereas others took place closer to 6,000–7,000 y ago, such as Yangtze China (68) and perhaps central America (cf. 69). Agriculture developed 4,000–5,000 y ago in the savanna habitats of Africa (70), India (71), Southeast Asia (72), and the North American forests and savannas

(73, 74). Although some pathways led from sedentary hunter-gatherers to early farmers, as in Southwest Asia or Yangtze China (68), others shifted from mobile hunting to the addition of herding first, for example in Africa (70), or from mobile hunting and gathering to mobile forms of agriculture like shifting cultivation, as in India (75), New Guinea (76), or South America (77).

Widespread agricultural land use by mid-Holocene is further evidenced by altered fire regimes that may have transformed vegetation structure and species composition across many regions, with woodland ecosystems from the Mediterranean to the Tropics increasingly recognized as the bio-cultural legacies of long histories of prior human use (50, 74, 78–84). Another general legacy of agricultural land use has been the creation of anthropogenic soils (anthrosols) (85), including the manure-enriched "plaggen" soils of Northwestern Europe, which may date to 4000 B.C. (86), the "terra preta" of the Amazon basin enriched with charcoal dating perhaps to 500 B.C. (87) and potentially in Africa (88), together with a wide range of anthrosols altered by sustained tillage, irrigation, manuring, and other land-use practices (83, 89).

In Southwest Asia (by 7000 B.C.) and Europe (by 5000 B.C.), the early presence of intensive land-use technologies has been confirmed by stable nitrogen isotope ratios in preserved crop grains, indicating that manures were used to sustain intensive cultivation near settlements (90, 91). In China, historical evidence supports a long and gradual history of extensification and later intensification of rice production, even though advanced technologies were available early (92). Similarly, as rice agriculture gradually spread southward and westward, reaching Thailand and northern India by 2000 B.C., less intensive rainfed and naturally inundated systems were first used (72), followed much later by more intensive systems (44).

Adaptive Intensification and the Rise of Agricultural Populations

The early presence but limited application of more productive agricultural land-use technologies agrees with the classic theory of induced intensification, in which technology adoption is driven not by rates of technological innovation but by demographic pressures for increased agricultural yields as populations increase and land becomes scarce (24, 34, 39). Although existing archaeological and historical evidence seems to support this theory in general, data are not currently available at the levels necessary to quantify the status of agricultural land-use intensification in specific regions and time periods across the Holocene. Nevertheless, the evidence is clear that agricultural human populations had spread across most continents by the mid-Holocene, leading to the clearing of native vegetation and herbivores, their replacement with domesticates, and the increasingly intensive application of techniques and inputs to enhance the productivity of land as populations became denser (44, 61).

The rise and dispersal of agricultural populations across Earth's land was likely driven by increasing rates of population growth sustained by early agricultural economies (93–95), which likely enabled them to dominate Earth's most productive landscapes, where increasingly intensive agricultural systems became established in most regions of the world, despite the periodic collapse of individual societies and their land-use systems (96). By the 1500s and even earlier in some regions of Asia and Europe, agricultural productivity had reached remarkable levels through intensive use of a wide variety of highly developed technologies, including irrigation, multiple cropping, crop rotations incorporating legumes, and a wide range of fertilizers, including manures, ashes, and even commercially traded oil seed cakes (44, 92). In less densely populated regions, agricultural productivity was generally much lower, as in the pre- and postcolonial Americas, Australia, and New Zealand (44, 45, 74). Agricultural yields within the most densely populated and productive preindustrial land-use systems compared well with modern yields and were sustained in some regions for centuries to millennia, even though they also tended to require extreme inputs of labor and other socially unsustainable hardships (43–45, 92). At the same time, the advent of increasingly productive land-use systems expanded opportunities for agricultural surplus extraction by trade and taxation, enabling the rise of nonagricultural populations in urban societies.

Urbanization, Industrial Land-Use Intensification, and Forest Recovery

The first urban populations dependent on trade for their sustenance emerged as early as 4000 B.C. in the Near East and became common across the Indus Valley, Egypt, and China by 1500 B.C. (97), with major cities (populations >100,000) developing by 2000 y ago in the Near East, Europe, and Asia (14). Still, the scale and rate of urbanization over the past two centuries is unprecedented, with the percentage of human populations living in cities growing from approximately 7% in 1800, to 16% in 1900, to more than 50% today (19).

Concentrating human populations within cities transforms the economies of scale in human interactions, producing higher average incomes and enabling a wide array of novel social benefits as urban systems advance (98, 99), which in turn enable further growth and help to drive rural–urban migration (100, 101). The massive food and resource demands of large, wealthy, and growing urban populations require high levels of agricultural surplus production and trade, which tend to be met by increasingly intensive and productive agricultural systems concentrated in Earth's most productive agricultural lands, supported by ever larger scales of farming operations, trading systems, and technological institutions (44, 102). Although similar processes have operated since the emergence of urban populations, recent rapid urban growth has been supported by the rise of high-yielding industrial land-use systems sustained by large energy subsidies from fossil fuels and other industrial inputs, accelerating through the "green revolution" of the 1950s and continuing today (44).

Despite their unprecedented scale, sophistication, and productive capacity, the rise of intensive industrial land-use systems fits well within our general definition of land-use intensification (Fig. 3), with increasing human population densities, concentrated within urban settlements in this case, driving ever increasing productivity per unit area of land. Industrial technologies, especially mechanization, have also largely decoupled human labor from productivity increases, enabling an unprecedented proportion of human populations to live within cities, which even today occupy less than 1% of Earth's ice-free land (19). These major increases in agricultural productivity have meant that recent dramatic growth in human populations and richer diets have not translated into an acceleration of per capita demand for arable land, but rather to a stabilization or even a decline in this key indicator of human-driven environmental change (103, 104). As agriculture continues to intensify and migration to cities depopulates rural landscapes, lands less suited to industrial-scale production are being abandoned in some regions, enabling large-scale forest recoveries, especially where governance systems support this (84, 105, 106).

Major Global Consequences of Early Land-Use Intensification

Climate Change. A major reason why land-use history is significant to understanding anthropogenic global change processes is the strong interaction between land cover and climate (8). Vegetation cover changes caused by land use can alter regional and global climate through both biogeochemical (emissions of greenhouse gases and aerosols) and biogeophysical (albedo, evapotranspiration, and surface roughness) feedbacks with the atmosphere, with reverse effects following land abandonment, reforestation, and other vegetation recoveries (107). As a result, the very different land-use histories produced by different models of Holocene land-use change (Figs. 1 and 2) have major implications in understanding the emergence of humans as a global-scale force transforming climate—a key indicator of Earth system transformation and the emergence of the Anthropocene (9–11).

The Early Anthropogenic Hypothesis (108) posits that mid-Holocene increases in CO_2 and CH_4 resulted from early land clearing and other agricultural practices and that these unprecedented interglacial trends in atmospheric composition set global climate on a trajectory toward warmer conditions long before human use of fossil fuels (108, 109). Furthermore, deforestation in the middle–high latitudes might have amplified Little Ice Age cooling by exposing more snow and increasing surface albedo (107, 110, 111). Modeled regional and global climate responses to simulated (107, 110, 111) and reconstructed historical land cover changes over the past century (112) and millennium (113) generally agree that anthropogenic deforestation drives biogeophysical cooling at higher latitudes and warming in low latitudes and suggest that biogeochemical impacts tend to exceed biogeophysical effects (113). However, most simulation studies are based on a narrow set of land cover reconstructions over at most one millennium and do not incorporate the effects of land use and its intensification across the Holocene. As a result, hypotheses relating human activity to historical climate change have yet to be tested rigorously under the full range of plausible historical conditions (4, 24).

Regardless of whether early land use significantly affected global climate, understanding the global role of land use in determining the onset and magnitude of anthropogenic climate change is critical for gauging the climatic impact of current and future modifications of the terrestrial biosphere, including efforts to offset fossil fuel emissions by reducing deforestation (114). Although projected increases in greenhouse gas concentrations caused by fossil fuel combustion are expected to dominate 21st century climate change, some studies suggest that anthropogenic land use may yet be at least as important and may remain so in the near future (8).

Ecosystem Transformation. Early human use of land has profound implications for ecological science and conservation. The first and foremost is that many, and perhaps most, terrestrial ecosystems have been altered by sustained direct interactions with human populations and land-use systems since the late Pleistocene or early Holocene (13, 14, 115). The most densely settled and intensively used agricultural landscapes tend to be the mostly profoundly and permanently transformed by the impacts of land clearing, soil tillage, increased erosion and runoff, nutrient enrichment, domesticated species, and unintentional species introductions (23, 115). However, even in less intensively used systems, exotic species tend to become established more frequently and permanently (116), and increased fire frequencies are associated with low human population densities and fire suppression with higher population densities (117), among other impacts (115). To be effective in conserving ecosystems and biodiversity altered by millennia of human interaction, ecological science and conservation will need to go beyond the view of humans as a recent disturbance and incorporate a solid theoretical and historical understanding of the dynamics of human populations and land-use systems and their role in shaping ecosystems over the long term (83, 115, 118).

Confirming the Past: A Quantitative Global Archaeological History of Land Use?

Global models reveal that the importance of land use as a global change process across the Holocene hinges largely on our understanding of the long-term dynamics of land-use intensification processes (Figs. 1 and 2). Review of existing archaeological evidence has demonstrated that land-use intensification processes were widespread across the Holocene and perhaps even the late Pleistocene. However, these two lines of evidence alone remain insufficient to conclusively determine the global extent of land use in different periods across the Holocene.

The tools of archeology and paleoecology have enabled long-term reconstructions of population and land-use histories across a wide variety of Earth's landscapes (e.g., refs. 74 and 119–121). Land use and its ecological impacts can be diagnosed from archaeological and paleoecological plant and animal remains, including pollen and phytoliths (70, 72). Combustion processes often leave signs of land use and related human activities, including enhanced fire rates and forest clearing (122) and the preindustrial use of harvested biomass for fuel (53, 117). Agricultural practices, including tillage, manuring, burning, composting, and use of chemical fertilizers, alter the chemistry and isotopic composition of nitrogen and phosphorus in soils and plant and animal remains (85, 89, 90). Direct human alterations of geomorphology and hydrology, including irrigation systems and other earthworks, are also useful indicators of human use of land, together with changes in the rates and spatial patterns of soil erosion and sedimentation rates in terrestrial, coastal, and lacustrine environments (7).

However, even the best field studies of long-term ecological and archaeological changes at specific sites are subject to methodological and empirical limitations and uncertainties (123), and studies must be scaled appropriately to serve as local representatives of global change in larger synthetic studies. As a result, despite the availability of suitable tools and abundant studies at local scales, the global history of land use and its intensification over the course of the Holocene cannot be assessed without a far more comprehensive, spatially detailed, quantitative, and accurate global assessment of population and land-use histories than has ever yet been attempted. Accomplishing this will require new geospatial tools and sustained efforts to collate, georeference, and harmonize existing archaeological and paleoecological data acquired at sites around the world and to collect new data for sites and regions currently underrepresented in the global paleoenvironmental record (124). Although the scale of these efforts would require unprecedented levels of support, standardized global sets of local historical land use and population reconstructions might ultimately enable strong empirical testing of the global importance and historical dynamics of land use as a force transforming the terrestrial biosphere across the Holocene.

Lessons from the Past and for the Future

Results from the first spatially explicit quantitative global land-use models over the course of the Holocene demonstrate that land-use intensification is a potentially pivotal process in both regulating the ecological impacts of human populations and in sustaining their global growth from the beginning of the Holocene to the present day. If, as suggested by intensification theory and archaeological data, land-use intensification was gradual across the Holocene, the results of historical modeling reveal an Earth significantly transformed by land use by 1000 B.C., with significant areas on nearly every continent now in recovery from past historical peaks of land use (Fig. 1*B*). Alternatively, if land use per capita has been fairly constant across the Holocene, early land use was mostly localized and globally insignificant and accelerated greatly only in recent centuries (Fig. 1*A*). Although the evidence from archaeology and environmental history point toward the former view of land-use history, available data remain far from adequate to quantify the global significance of land use and intensification processes over the long term. The paleohistory of anthropogenic change across much of the Americas is especially unclear and controversial (e.g., refs. 74, 82, and 125) and may be exceptional compared with other continents. Nevertheless, the implicit view from the Anthropocene that humans have reached a historical moment in which "wild nature" is threatened by an accelerating and unchecked expansion of human use of land is challenged by a view that humans are ancestral shapers and stewards of Earth's terrestrial surface (82, 83).

Intensification processes may be even more important to understanding the future of land-use change as a force transforming the Earth system. Recent studies indicate that, depending on location, there is still strong potential for further intensification of agricultural land use (22, 104, 126). Although these and other recent assessments of the Earth's capacity to support further population and consumption growth are optimistic, there remain a wide array of societal challenges in adapting land systems to meet growing demands (104). Some of Earths' most fertile lands are rapidly undergoing large-scale conversions to urban areas (102). Global market integration has increased connectivity between world regions, with regions having the highest demand for land resources often experiencing agricultural abandonment and reforestation while displacing their production needs to less developed regions (127), mirroring patterns from the colonial era. Rapid development of highly capitalized demands on land resources now drive massive rapid shifts in land systems, limiting our capacity to predict future land-use changes (128).

The single most important lesson from assessing changes in land use across the Holocene is that changes in the productivity of land-use systems, and especially productivity per area of land, has likely been the main long-term driver of change in human impact on the terrestrial biosphere. The pace of agricultural intensification is, therefore, also likely to remain a major determinant of future land change and our ability to meet societal demands for food, feed, housing, and energy (104). Today, as populations, consumption, and technological power advance at an exponential pace that might seem almost impossible to sustain, especially given current societal dependence on fossil energy, increasingly intense land-use systems seem to be evolving in new, more land-efficient, directions that may even reverse many of the environmental impacts of prior land use.

Methods

Global land use and population datasets divided into five arc minute grid cells (spatial resolution ~85 km^2 at the equator) were obtained for the HYDE 3.1 (19, 31) and KK10 (4) global land-use models. These data were analyzed using a Geographic Information System to estimate global areas and populations within a simplified set of terrestrial biomes (aggregated from the potential vegetation classes of ref. 28) and world regions (after ref. 1). Maps depicting first significant land use were produced by overlaying maps of cells with land-use areas >20% of land area within each cell at each time period (20% criteria for significant land use as per refs. 1 and 115), for all cells where A.D. 2000 land use was also >20% of land area in each cell (earliest at the top; Fig. 1). These maps were then overlaid on maps depicting recovery from peak land use in each cell, assessed as the difference between A.D. 2000 land use and the historical maximum percentage land use (Fig. 1).

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