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Using the Planet

Introduction

200,000 years ago, Homo sapiens arose in Africa amid other tool-making, fire-using species of the genus Homo (Sterelny 2011). It would be another 100,000 years before H. sapiens distinguished itself from prior species by rapidly expand its range across the planet, leaving a trail of culturally advanced archaeological evidence (Kirch 2005, Sterelny 2011, Henn *et al*. 2012). By the end of the Pleistocene, human populations were well established across Earth's habitable regions, sustaining themselves using an astonishing array of sophisticated socially transmitted technologies within ecosystems already reshaped by their ancestors to enhance their productivity (Kirch 2005, Ellis *et al*. 2013). Even before the advent of agriculture, H. sapiens had initiated an entirely new process of planetary change. Earth would never be the same.

Recent global changes in Earth's atmosphere, climate, lithosphere and biosphere are unprecedented in human history, if not the history of the planet, prompting the call to recognize the Anthropocene as a new geological epoch starting with the rise of the Industrial Revolution (ca. 1850) or its "Great Acceleration" since 1950 (Steffen *et al*. 2011, Syvitski 2012). Yet the evidence from archaeology, paleoecology and environmental history is clear: human societies have been reshaping the terrestrial biosphere, and perhaps even global climate, for millennia (Kirch 2005, Ellis 2011, Ellis *et al*. 2013, Ruddiman 2013, Smith and Zeder 2013). The entire Holocene might simply be renamed the Anthropocene (Ruddiman 2013, Smith and Zeder 2013).

Formal recognition of the Anthropocene is ultimately a decision for geologists. Nevertheless, global change science has much to learn by viewing humanity's role in Earth-system dynamics through the lens of geologic time. By focusing on the dramatic changes of the past two centuries, prior anthropogenic changes have been discounted as localized, globally insignificant and of little value to understanding contemporary processes of global change. This is a major oversight. Though industrial systems are now driving massive changes across the Earth system, the long-term transformation of the terrestrial biosphere by human populations and their use of land is no less massive, and likely represents the single greatest anthropogenic global change yet wrought by humanity (Ellis 2011, Ellis *et al*. 2013, Smith and Zeder 2013). Still, the most important reason to explore the long-term dynamics of human transformation of the terrestrial biosphere is to better understand the social processes that have made it possible for a single species to alter the course of Earth's history (Ellis and Haff 2009, Ellis 2011, Ellis *et al*. 2013).

A tale of two planets

Recently, two different spatially explicit global reconstructions of human populations and their use of land across the Holocene have been developed that enable quantitative assessment of the long-term dynamics of human use of the terrestrial biosphere for the first time (Fig. 1 (Ellis 2011, Ellis *et al*. 2013). While contemporary global patterns of land use and population are reconstructed using data from census and remote sensing, land use prior to historical records (ca. 1700 in most regions) must be "backcasted" from contemporary patterns using models of per capita land use. As is evident in Fig. 1, the results of these two reconstructions are so different that they might as well come from two different planets: one with ancient and extensive human use of land (KK10; Kaplan *et al*. 2011) and one with land use becoming globally significant mostly in recent centuries (HYDE; Klein Goldewijk *et al*. 2011). HYDE predicts that outside Europe's more developed regions, human use of land was insignificant before A.D. 1750. In KK10, land use is globally significant far earlier in the Holocene, with more than 20% of Europe and Asia already in use by 3000 B.C., and large areas of Earth's land in recovery from higher levels of land use in earlier periods.

The difference? HYDE, the first and most popular Holocene land use reconstruction, assumes that land use per capita remained nearly constant over time. KK10 takes an entirely different approach,

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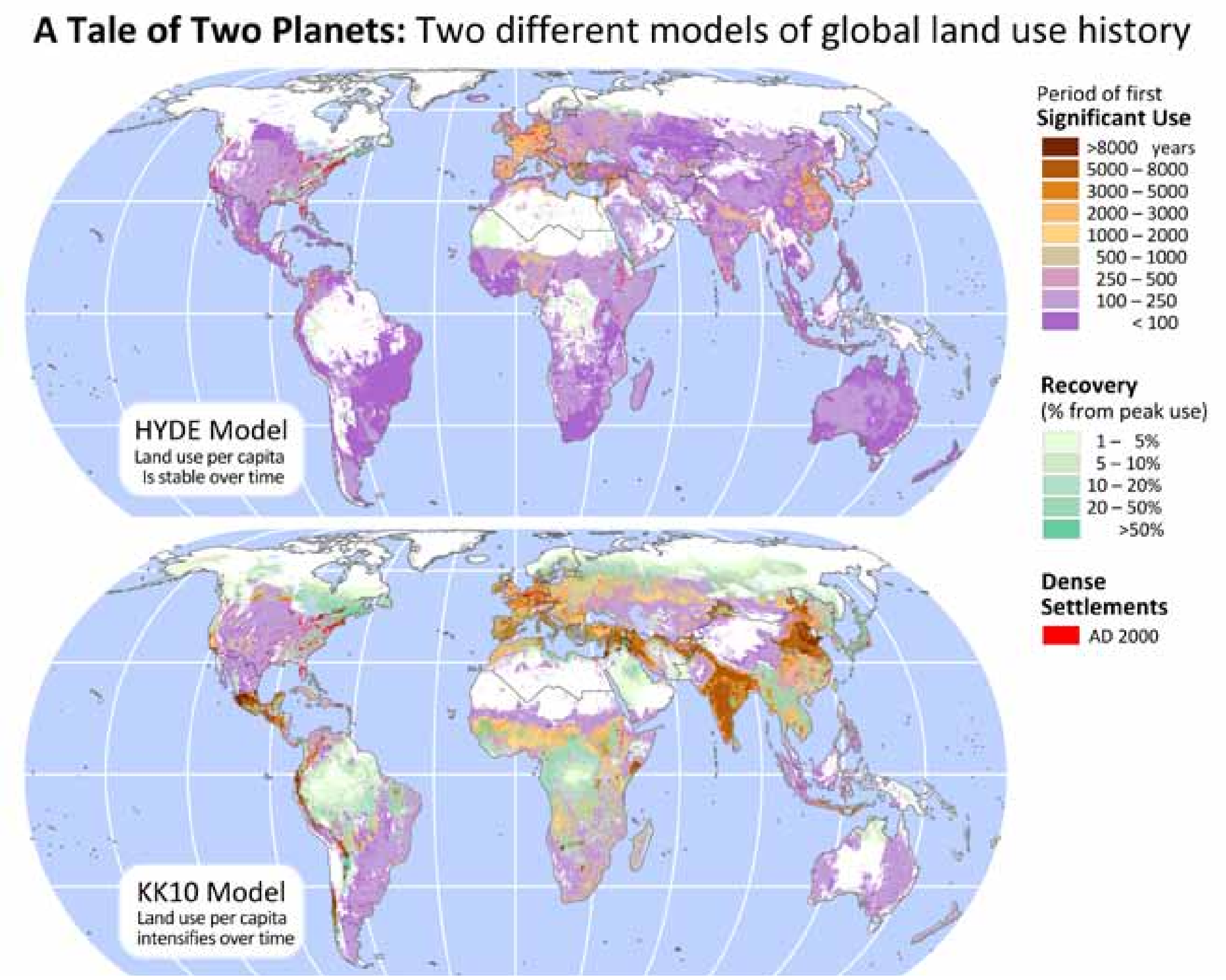

Figure 1: *Global maps of land change history based on historical reconstructions from the HYDE and KK10 models (After Fig 1. in (Ellis et al. 2013). Time period of first significant land use and recovery from peak land use, 6000 B.C. to A.D. 2000,*

estimating land use from population by means of empirically derived nonlinear relationships with population density, such that low-density populations with high per-capita land use first expand to fill all usable land and then intensify their use of land (use less land per capita) as population densities increase over time.

So which model comes closer to the truth? At present, it is not yet possible to conclusively validate global models of Holocene land use against empirical data. The massive task of compiling and standardizing the requisite archaeological and paleoecological data has yet to be undertaken. Nevertheless, by comparing existing models with what we know from archaeology, paleoecology, geography, and environmental history, it is clear that by incorporating adaptive changes in land-use per capita over time, a more spatially detailed and plausible assessment of our planet's history is revealed, with a biosphere long ago affected by humans. Land-use intensification is potentially pivotal in understanding human transformation of the Earth system (Ellis *et al*. 2013).

Land use intensification as a global change process

Broadly defined, land-use intensification is the adaptive response of human populations to demographic, social and/or economic pressures leading to the adoption of increasingly productive land-use systems (Ellis *et al*. 2013). Put simply, humans don't make the effort to use land efficiently unless they must, to feed growing populations on the same land, or to satisfy social or commercial demands. Though land use intensification tends to drive general increases in land productivity as populations grow, with low density populations using more land per capita than denser populations, the relationship between any given population and the productivity of its land-use systems is dynamic and multidimensional, driven not only by population but also by social and economic processes regulating resource demand, land availability and suitability, barriers to technology adoption and availability, and the potential for intensive use of land to degrade its productivity over time. As a result, a general trend towards increasingly productive use of land is produced not by a smooth and continuous process, but through a complex succession of land system regime shifts, some of them regressive, subjecting populations to both surplus production and productivity crises as illustrated in Fig. 2.

Land use intensification began early, long before the Holocene. Archaeological evidence in the form of plant and animal remains, charcoal, isotopic records and other legacies demonstrate that human hunter-gatherers long ago engaged in pre- and proto-agricultural land use intensification practices to support larger populations on the same land, including dietary broadening (eating more species once preferred megafauna were rare or driven extinct), burning vegetation to enhance hunting and foraging success (ecosystem engineering), processing plant and animal foods to enhance nutrient availability (cooking, grinding, etc.), and the propagation of useful species (Kirch 2005, Ellis *et al.* 2013). As a side effect, these practices likely facilitated increasing reliance on grasses and other species that would later become crops, putting them on the road to domestication (Ellis *et al.* 2013).

Pre-agricultural technologies for ecosystem engineering were much less productive than the agricultural technologies that replaced them. Nevertheless, they still enabled human populations to grow far beyond the capacity of unaltered ecosystems to support them. As populations grew, more intensive land-use practices were adopted to sustain them or populations migrated to areas with less intensive use (extensification), including uninhabited wildlands. By the early Holocene, hunter-gatherers had expanded their populations across the Earth and required early land use intensification processes to survive and to grow and lived mostly within ecosystems that had already been transformed by their ancestors to enhance their productivity, setting the stage for the rise of agriculture.

To make a long story short

Agricultural populations grew more rapidly than those of hunter-gatherers, ultimately replacing them across Earth's most productive lands. Intensification continued, with long fallow shifting cultivation replaced by systems with

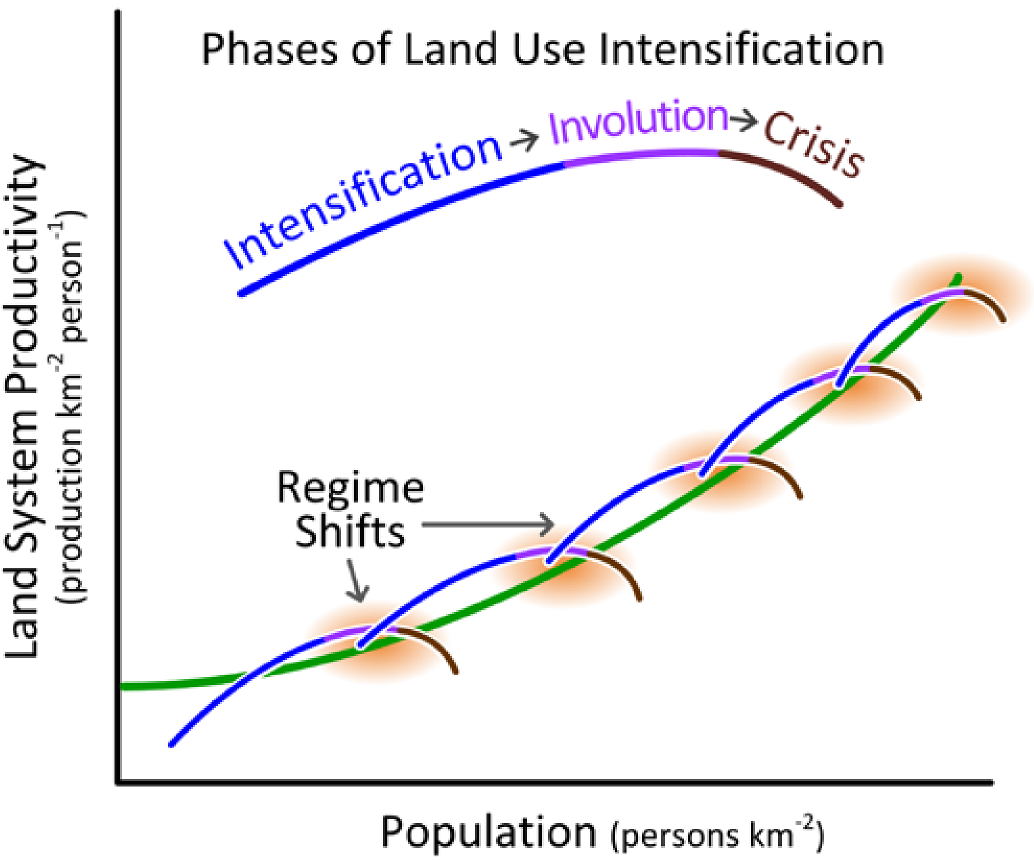

Figure 2: *A general model of adaptive land use intensification (After Fig 3 in (Ellis et al. 2013). Arcs depict individual land-use systems with three phases: Intensification (technologies enable productivity to increase faster than population), Involution (technology-driven productivity increases become exhausted, such that only net increases in labor or other costly inputs enable increases in production), and Crisis (all capacity to enhance land productivity is exhausted and food production cannot keep up with increasing populations). Regime shifts drive changes from less to more productive land systems. Green line highlights general trend toward increasing productivity with population.*

shortened fallows, and eventually continuous cropping enhanced by the plow, irrigation, manuring and other increasingly productive land use technologies. Intensive agricultural systems gradually proliferated across Earth's most productive lands, supporting densely populated villages and eventually supplying food surplus to growing urban populations. As the demands of urban populations grew, they were sustained by ever larger scales of farming operations, trading systems, and technological institutions, ultimately leading to the high-yielding industrial "green revolution" land-use systems by the 1950s and continuing today, sustained by fossil energy and other industrial inputs.

Industrial technologies, especially mechanization, have increasingly decoupled human labor from productivity growth in agriculture, thereby allowing the majority of human populations to live in urban areas for the first time. Increasing agricultural intensity has also helped prevent rapid population growth and progressively richer diets from translating into accelerating per capita demand for arable land- an indicator that may now be leveling off (Ellis *et al.* 2013). As agriculture continues to intensify and migration to cities depopulates the rural landscapes of many regions, lands less suitable for industrial-scale agricultural are being abandoned, allowing forests to recover in regions where economics and governance systems support this.

Global consequences.

Land clearing by hunter-gatherers and farmers, soil tillage, and wet rice production all emit major amounts of carbon dioxide and methane. As a result, early human use of land might have initiated global changes climate long before human use of fossil fuels (Ruddiman 2013). While this "Early Anthropocene" hypothesis remains an active area of research (e.g. Kaplan *et al.* 2011), understanding the role of early land use in determining both the onset and magnitude of anthropogenic climate change is necessary to evaluate the biosphere's role in both current and future climate change, including the prospects for biofuels and reduced deforestation and tillage to mitigate carbon emissions from fossil fuels.

The effects of human populations and their use of land on biotic communities and ecosystem processes are increasingly recognized as profound and persistent over periods from centuries to millennia. Evidence is growing that many habitats once thought to be only recently disturbed by human activities actually represent the bio-cultural legacies of human interactions over millennia. While the most densely settled and intensively used landscapes tend to be the most altered, even the least intensively used rangelands, seminatural ecosystems and seemingly undisturbed areas with proximity to human populations share a tendency toward biotic communities and ecosystem processes transformed by exotic species invasions, altered fire regimes, nutrient pollution and other pervasive human influences (Ellis 2011, Hobbs *et al.* 2013). Efforts to acknowledge this profound and extensive human influence is now leading to a wholesale rethinking of ecological science and conservation to reflect the essential long-term role of humanity as permanent stewards of the biosphere (Hobbs *et al.* 2013).

Learning from the ancestors.

The first spatially explicit global histories of land-use across the Holocene make clear that land-use intensification has played an essential role by enabling human populations to grow well beyond the capacity of the unaltered biosphere to support them (Ellis *et al.* 2013). Despite major setbacks from epidemic disease and social collapse (Butzer and Endfield 2012), the global growth of human populations has been sustained from millions at the start of the Holocene to billions today.

Our species has been changing the planet at global scales since the late Pleistocene. As a result, we have inherited a used planet from our ancestors. Unlike prior geological time periods, the long-term driving forces of global change in the Anthropocene are not within the realm of physics, chemistry, or even biology. The ultimate drivers of the Anthropocene are inherently social, emerging from H. sapiens' unprecedented ability to accumulate and transmit adaptive technological and social innovations across individuals, societies and generations (Ellis and Haff 2009, Ellis 2011, Sterelny 2011, Ellis *et al.* 2013). As a key social process of the Anthropocene, land use intensification has been essential to sustaining the emergence of large, technologically sophisticated, affluent, and interconnected societies with the power to alter the course of Earth's history (Ellis *et al.* 2013). As we move deeper into the Anthropocene, strengthening our scientific understanding of the long term social processes that sustain humanity has never been more important.

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