ARCHAEOLOGY

Archaeological assessment reveals Earth's early transformation through land use

ArchaeoGLOBE Project*†

Environmentally transformative human use of land accelerated with the emergence of agriculture, but the extent, trajectory, and implications of these early changes are not well understood. An empirical global assessment of land use from 10,000 years before the present (yr B.P.) to 1850 CE reveals a planet largely transformed by hunter-gatherers, farmers, and pastoralists by 3000 years ago, considerably earlier than the dates in the land-use reconstructions commonly used by Earth scientists. Synthesis of knowledge contributed by more than 250 archaeologists highlighted gaps in archaeological expertise and data quality, which peaked for 2000 yr B.P. and in traditionally studied and wealthier regions. Archaeological reconstruction of global land-use history illuminates the deep roots of Earth's transformation and challenges the emerging Anthropocene paradigm that large-scale anthropogenic global environmental change is mostly a recent phenomenon.

Human societies have transformed and managed landscapes for thousands of years, altering global patterns of biodiversity, ecosystem functioning, and climate (*1*–*6*). Despite increasing interest in the early global environmental changes caused by human activities, from changes in fire regimes and wild animal and plant populations by hunter-gatherers to increasingly intensive forms of agriculture, the global extent, intensity, temporal trajectory, and environmental consequences of Earth's transformation through human land use remain poorly understood outside the archaeological community (*7*–*9*).

Human transformation of environments around the world began with late-Pleistocene hunting and gathering societies and increased throughout the most recent interglacial interval with the emergence of agriculture and urbanized societies. Agricultural land use is implicated in anthropogenic global environmental changes ranging from greenhouse gas emissions and climate change (*5*, *6*, *10*) to widespread deforestation, soil erosion, and altered fire regimes, as well as species introductions, invasions, and extinctions (*4*, *8*, *11*). Such changes are evident even in tropical rainforests and savanna environments long considered pristine (*12*, *13*). However, existing models of long-term changes in global land use (*5*, *14*, *15*) differ substantially in their representation of these early transformations (*8*, *16*), largely owing to limited incorporation of disparate empirical data from archaeology and palaeoecology (*17*, *18*). As a result, global models and assessments of early anthropogenic influence on climate, habitats, biodiversity, and other environmental changes remain poorly characterized (*4*, *10*, *18*, *19*).

Efforts to map land-cover change over the past 10,000 years from pollen data have increased during the past decade, and high-quality regional reconstructions are now available for Europe and the Northern Hemisphere (*20*–*24*). However, global reconstructions that combine both land-use and land-cover change using a range of data sources are rare (*18*, *25*) and have difficulty incorporating environmental data from archaeological sites (*26*). Here, we present a global assessment of archaeological expert knowledge on land use from 10,000 years before the present (yr B.P.) to 1850 CE, showing that existing global reconstructions underestimate the impact of early human land use on Earth's current ecology.

A global synthesis of archaeological knowledge

Archaeologists often study human alterations of environments, but most studies are qualitative or have a local or specialized topical focus [e.g., (*27*–*33*)]. To assess and integrate archaeological knowledge toward synthesis at a global scale, the ArchaeoGLOBE Project used a crowdsourcing approach (*34*, *35*). Archaeologists with land-use expertise were invited to contribute to a detailed questionnaire describing levels of land-use knowledge at 10 time intervals across 146 regional analytical units covering all continents except Antarctica. Contributors selected individual regions where they had expertise; 255 individual archaeologists completed a total of 711 regional questionnaires, resulting in complete, though uneven, global coverage (Fig. 1 and table S1). The result is an expert-based meta-analysis that uses semi-subjective (ranked) survey data to generate regional assessments of land use over time.

Regional-scale archaeological knowledge contributions were sufficient to assess land-use changes in all 146 regions between 10,000 yr B.P. and 1850 CE (Figs. 1 and 2). Overall, self-reported regional land-use expertise increased linearly from 10,000 yr B.P., peaked for 2000 yr B.P., and dropped off sharply thereafter (Fig. 2B), reflecting the decreasing emphasis on environmental archaeological methods in time periods with more abundant material remains and/or historical records. Quality of archaeological data pertaining to past land use (Fig. 2C), determined by the pervasiveness of archaeological surveys, as well as floral and faunal analyses in each region, followed a trend similar to that for expertise, although the peak was somewhat later and more pronounced, and the drop-off was less severe.

Global trends in expertise and data quality, and in published excavations, were heterogeneous across the globe, with consistently higher expertise and data quality across time in regions including, but not limited to, sections of Southwest Asia, Europe, Northern China, Australia, and North America, almost certainly reflecting a greater intensity of archaeological research in these areas. Other areas evidenced relatively low expertise among survey respondents and data quality until the most recent periods, especially parts of Africa, Southeast Asia, and South America.

Global patterns of regional land-use change

In 120 regions (82% of all regions, 88% of inhabited regions at 10,000 yr B.P.), foraging (practices of foraging, hunting, gathering, and fishing) was common (practiced across 1 to 20% of land in region) or widespread (practiced across >20% of region) at 10,000 yr B.P. and declined thereafter (Fig. 3, A and B). Foraging was less than widespread in 40% of all regions by 8000 yr B.P., a decline that expanded to 63% of regions by 3000 yr B.P. By 1850 CE, 73% of regions were assessed with less than widespread foraging, with 51% at the "minimal" (practiced across <1% of land in region) or "none" prevalence levels.

Regional trends of foraging (Fig. 4B and fig. S6D) reveal early declines from 10,000 to 6000 yr B.P. in Southwest Asia, with other regions exhibiting declines in foraging lifeways either gradually, beginning ~4000 yr B.P., or with hardly any declines at all until after 3000 yr B.P. This pattern is congruent with recent global assessments indicating that the majority of domesticated species appeared in the interval from 8000 to 4000 yr B.P., with a smaller number in earlier intervals (*28*).

The current dataset draws attention to the prevalence of agricultural economies across the globe (Fig. 4A) rather than focusing on centers of initial domestication, of which there are now at least 11 worldwide (*28*). At 10,000 yr B.P., these centers were limited to minimal or common components in parts of Southwest Asia. Subsequently, agriculture became much more widespread both through secondary dispersal from

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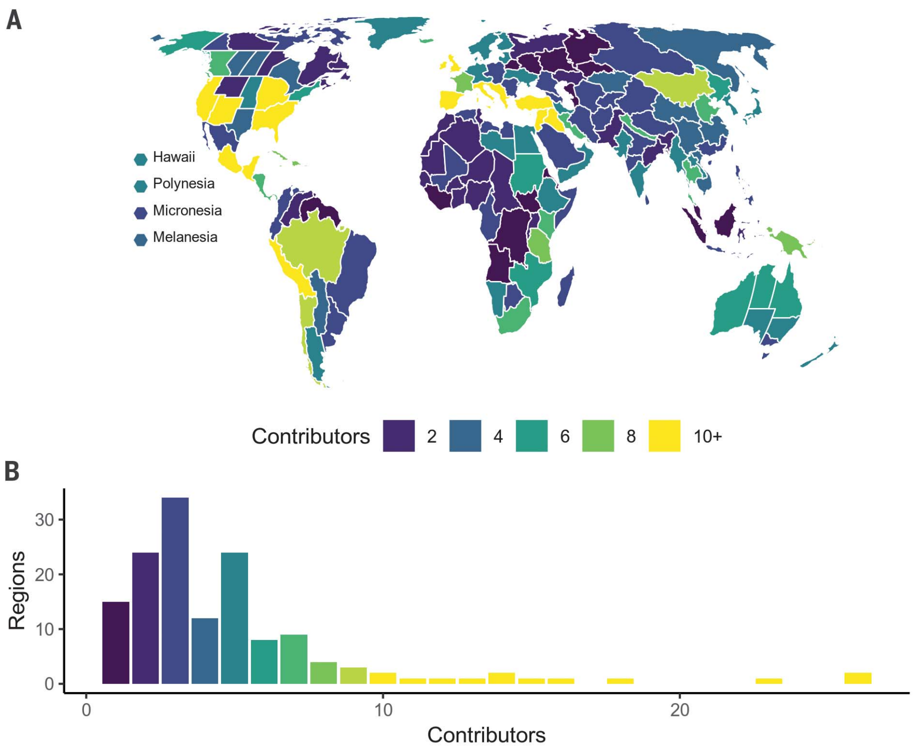

Fig. 1. Archaeological knowledge contributions. (**A**) Geographic distribution of knowledge contributions across 146 regions. The four island regions at left are aggregated into indicator panels with exaggerated areas (Eckert IV projection). (**B**) Histogram showing the distribution of 711 total contributions across regions.

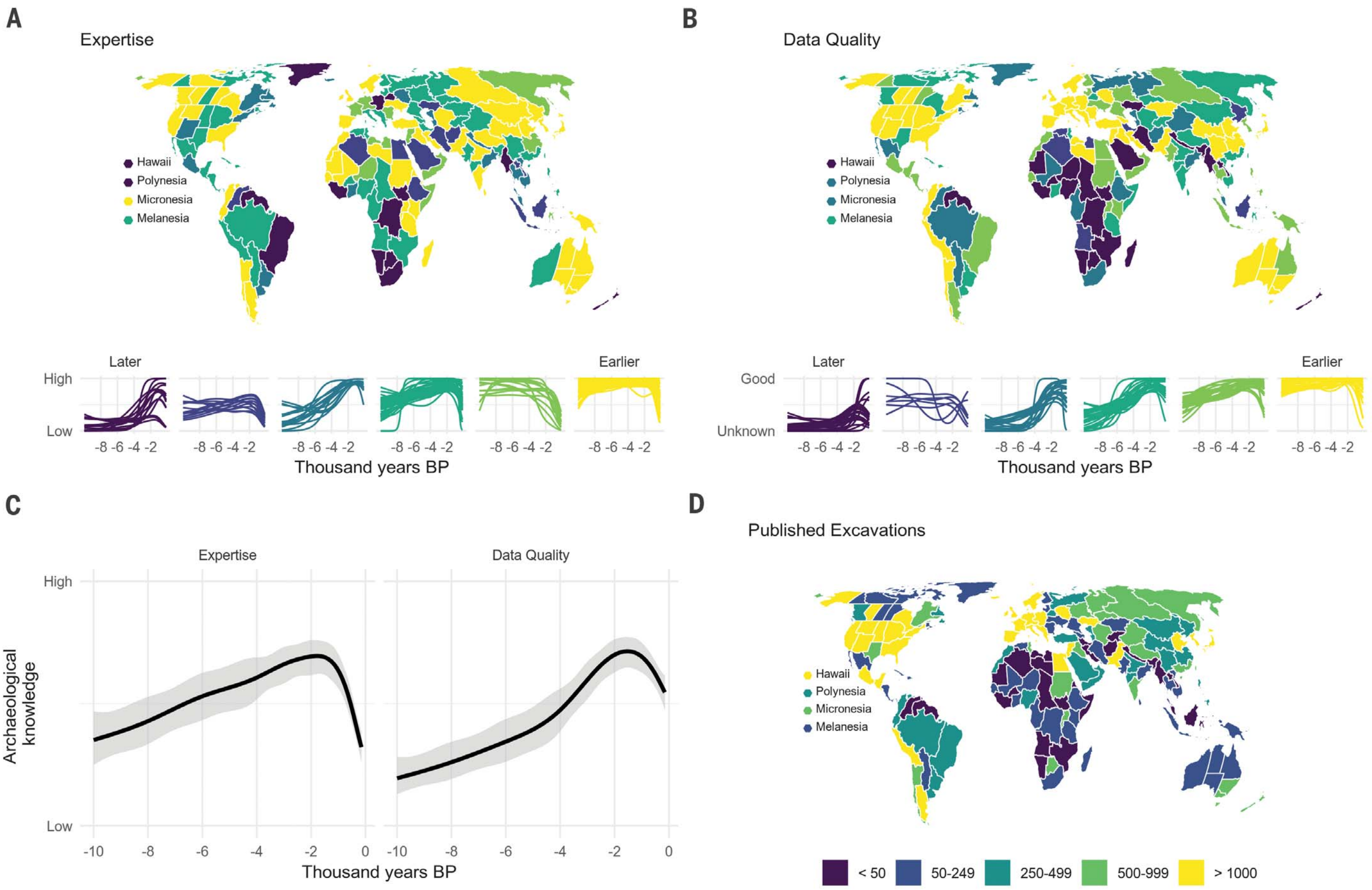

Fig. 2. Archaeological expertise, data quality, and published excavations. (**A**) Regional trends in land-use expertise estimated using a generalized additive mixed model, grouped according to a *k*-means clustering algorithm to show regions with similar temporal trends. (**B**) Regional trends in data quality. (**C**) Global trends in expertise and data quality with 95% confidence intervals. (**D**) Estimated number of published excavations per region.

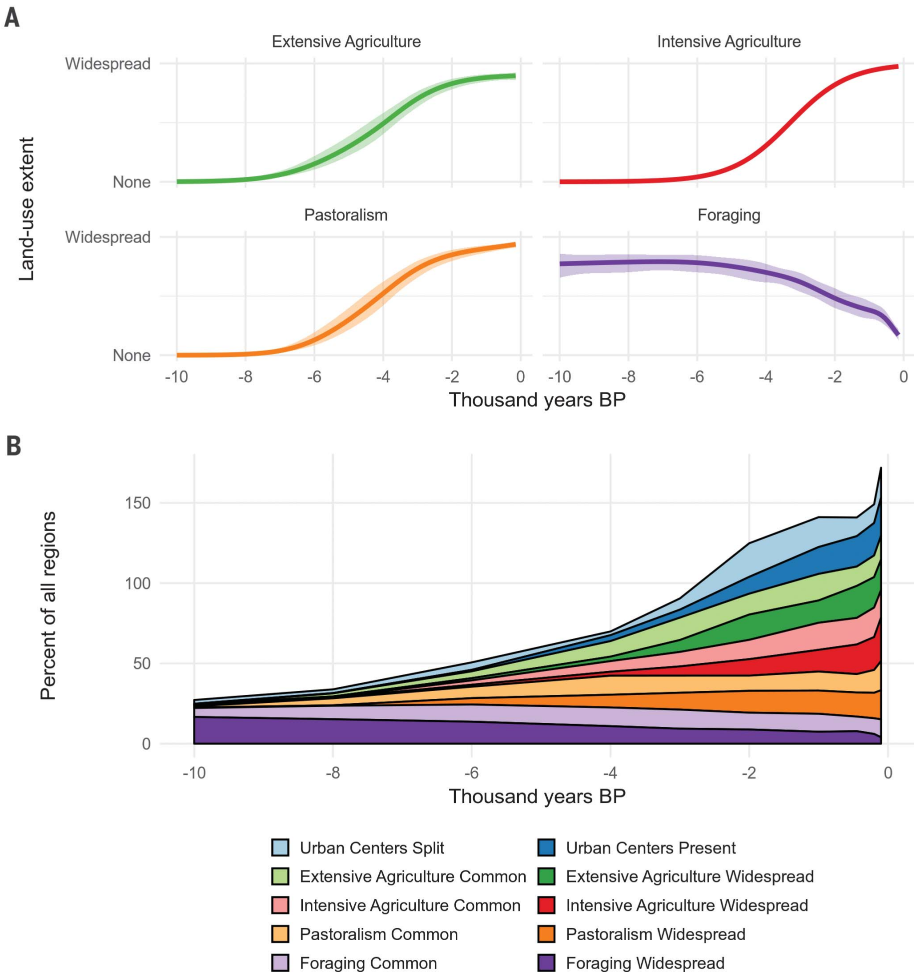

Fig. 3. Summary of global land-use trends. (**A**) Generalized additive mixed-model trends for the extent of each land-use type across all regions with 95% confidence intervals. (**B**) Cumulative summary of regions per land-use category based on consensus assessments (Common, >1 to 20% regional land area; Widespread, >20% regional land area), with presence or absence of urban centers. Categories are nonexclusive, resulting in plot values >100% for all regions.

Southwest Asia and eastern China and through new domestications in the Americas, New Guinea, and Africa. By 6000 yr B.P., 42% of land units had at least minimal extensive agriculture (swidden or shifting cultivation and other forms of noncontinuous cultivation), and it was common in >14% of units. Intensive agriculture (all forms of continuous cultivation) was geographically constricted (the Mediterranean, Southwest Asia, South Asia, and eastern China) and common in only a few regions (12 at 6000 yr B.P.) of suitable climatic conditions until 4000 to 3000 yr B.P., spreading more broadly only after 2000 yr B.P. (65 regions with at least common intensive agriculture at 2000 yr B.P.).

This study also illuminates the relationships between different modes of land use. Pastoralism was connected to agricultural centers of origin in Southwest Asia, East Asia, and the Andes, suggesting a close relationship between both types of production. By 10,000 yr B.P., both agriculture and pastoralism were established in the earliest source regions with a focus first around Southwest Asia and the Mediterranean, but by 8000 yr B.P., pastoralism had spread farther from Southwest Asia, perhaps because of the proximity of this region to arid environments where herding was more productive than farming (Fig. 4A). In the Americas, pastoralism was restricted to its origin in the Andes (present from 8000 yr B.P.) until after 1500 CE with the introduction of western domesticates.

After 6000 yr B.P., the geographic spread of extensive agriculture shows a markedly different pattern than that of pastoralism because of its dispersal from additional source locations in East Asia and the Americas. Over the same time period, pastoralism spread across northern Africa and central Asia and was common or widespread across much of Eurasia and Africa by 4000 yr B.P., including many regions where neither form of agriculture was common until between 4000 and 3000 yr B.P. Not until 3000 yr B.P. was extensive agriculture (75 regions) practiced commonly at a greater geographic scale than pastoralism (64 regions). Patterns of regional land use demonstrate the importance of pastoralist production across arid regions (Fig. 4A), including arid and northern regions where agriculture was unsuitable, and document that the type of management practiced on western Eurasian herd animals was highly adaptable and transferable.

Early onset of intensive land use: Assessments versus models

Regional onsets of intensive agriculture, described by archaeologists, were generally earlier than estimates of cultivated crop areas derived from the most commonly used, spatially explicit global reconstruction of land-use history [the HYDE dataset (*14*)]. ArchaeoGLOBE findings complement previous regional (e.g., Europe) land-cover studies based on palaeoecological data (*36*, *37*). Of the 130 ArchaeoGLOBE regions currently making up Earth's agricultural regions (regions with >1% crop area in HYDE at 2000 CE), 69 archaeological onsets were earlier when assessed at the "common" level, in regions encompassing 54% of global crop area at 2000 CE (Fig. 5C), and >67 were earlier at the "widespread" level (56% of global crop area at 2000 CE; Fig. 5D). Although 26 archaeological onsets at the common level were later than HYDE, including 13 regions later by >1000 years (8.4% of global crop area at 2000 CE), ArchaeoGLOBE onsets were >1000 years earlier in 27 regions encompassing 21.8% of global crop area in 2000. At the widespread level, archaeological onsets were later by ≤250 years in just three regions (5% of 2000 global crop area) and earlier by >1000 years in 21 regions, accounting for 22.0% of global crop area in 2000. By contrast, a comparison with KK10, a less commonly applied historical land-cover change reconstruction known for representing early agricultural transformation of land, showed generally earlier onsets of intensive land use than did ArchaeoGLOBE [fig. S7; (*15*)].

Discussion

The ArchaeoGLOBE dataset highlights broad patterns and consistencies in archaeological data while also identifying exceptions and knowledge gaps. Our data show geographical variability in total number of respondents, expertise level, and data quality, suggesting that the breadth of archaeological knowledge differs greatly from one region to another. Potential causes of geographical inconsistencies in archaeological knowledge include the varying conditions under which archaeologists work, the cumulative legacy and positive feedback of early research interests, and the physical accessibility (both real and perceived) of archaeological sites [see also (*38*)]. Although we made rigorous efforts to recruit archaeological knowledge contributions as widely as possible, biases in the dataset also derive from the anglophone orientation of key project investigators, as well as the limitations of their professional networks. These biases exacerbate historical geographical biases in the pursuit and construction of archaeological knowledge, including the application of environmental archaeological methods. ArchaeoGLOBE respondents may not form a representative sample of global archaeologists, but it is still clear that several regions have seen more intensive archaeological research. Regional hotspots of intensive study are concentrated heavily in Europe, Southwest Asia, and portions of the Americas, a pattern also observed for ecological field sites (*39*) and UNESCO World Heritage sites (*40*).

Regional cold spots that have received much less attention are concentrated in Southeast Asia and Central and West Africa, where resources available for archaeological fieldwork and training are limited. Nonetheless, experts in these regions were able to contribute generalized accounts of land-use trajectories. For instance, archaeobotanical investigations of the cultivation and domestication of indigenous cereals in sub-Saharan Africa (*41*–*43*) are beginning to shed light on earlier and more extensive forms of agriculture. Similar less-investigated indigenous agricultural practices likely characterize parts of Southeast Asia and northern India during the mid-Holocene [e.g., (*44*–*46*)]. Hence, the ArchaeoGLOBE project can help archaeologists prioritize future collection of empirical data and local capacity building to improve the reliability of global perspectives.

Deepening the Anthropocene

Archaeologists and anthropologists have broadly defined "domestication" and, to a lesser extent, "agriculture" [e.g., (*28*)]. However, "hunting and gathering" is a more varied and complex subsistence adaptation than originally conceptualized. Its definition generates debate among scholars by blurring countless variances in land use, resource management, and anthropogenic environmental change. Foraging, or "foraging/hunting/gathering/fishing," was used here to describe subsistence economies and land-use practices that generally exhibit lower amounts of direct human alteration of ecosystems and control of plant and animal life cycles [see (*47*)]. Within this broad category are many forms of resource procurement and land management that have drastically changed landscapes, and we now recognize that foragers may have initiated dramatic and sometimes irreversible environmental change [e.g., (*48*)]. In addition to altering biotic communities around the world through transport and propagation of favored species, extensive early land use by hunter-gatherers may also indicate widespread use of fire to enhance success in hunting and foraging (*49*). Systematic burning has implications for the global carbon cycle through increased greenhouse gas emissions, for water cycles through changes in vegetation and evapotranspiration, and for temperatures through changes in albedo (*50*, *51*).

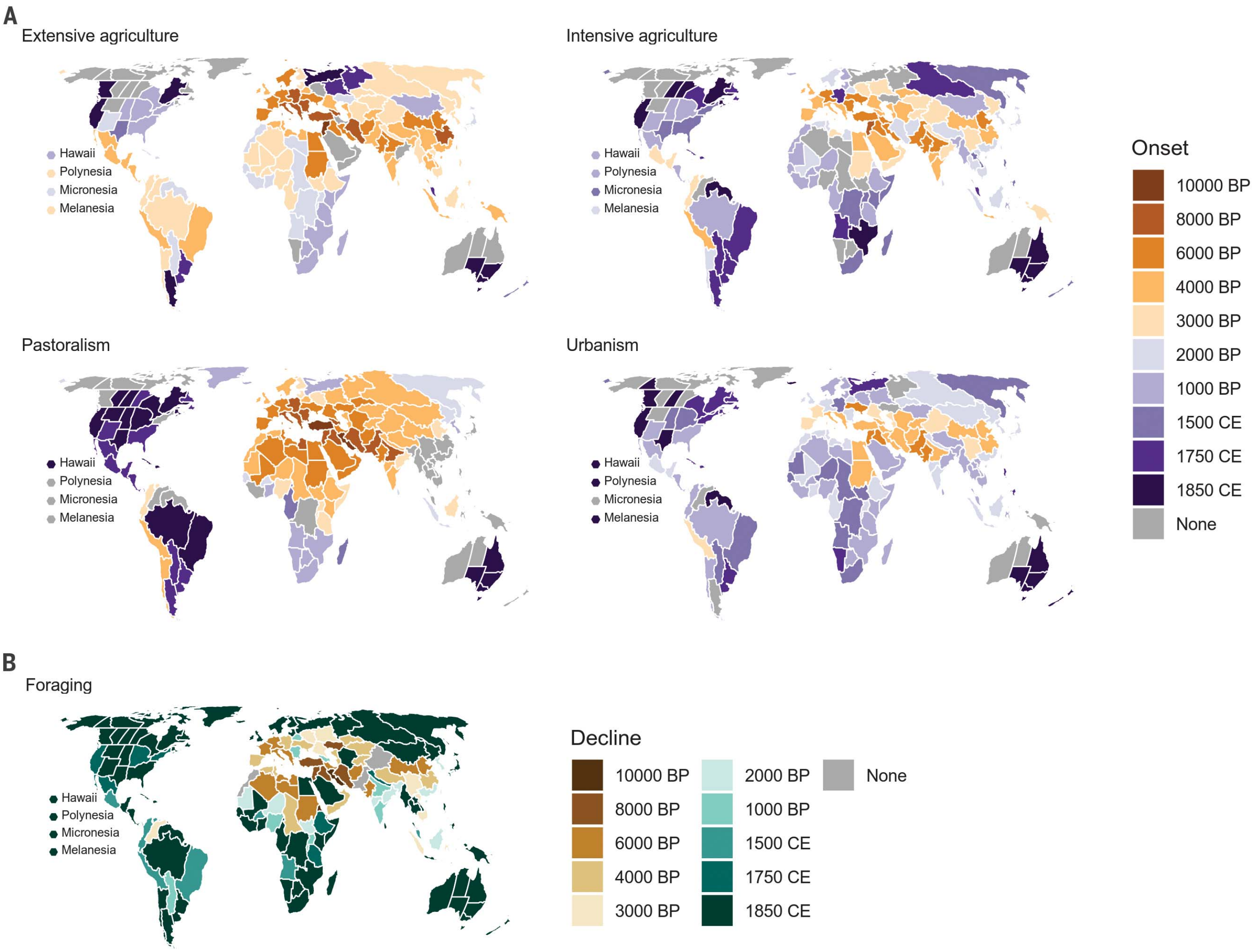

Fig. 4. Regional onsets of land-use categories and decline of foraging. (**A**) Onsets representing the earliest time step assessed at the "common" prevalence level (1 to 20% land area) for extensive agriculture, intensive agriculture, and pastoralism; the earliest time step was assessed as "present" for urbanism. (**B**) Decline representing the latest time step assessed at the "common" prevalence level for foraging.

Globally widespread evidence of hunter-gatherer land use indicates that ecological conditions across most of the terrestrial biosphere were influenced extensively by human activities even before the domestication of plants and animals. Although our dichotomous parsing of hunter-gatherers and agriculturalists is primarily operational, such divisions are still useful. Our data seem to support a unilineal trajectory toward increasingly intensive land use and the replacement of foraging with pastoralism and agriculture, a process that appears largely irreversible over the long term. Such trends also mask more complex pathways, as well as reversals at the local scale in numerous regions. In some parts of the world, agriculture did not simply replace foraging but merged with it and ran in parallel for some time, either as a

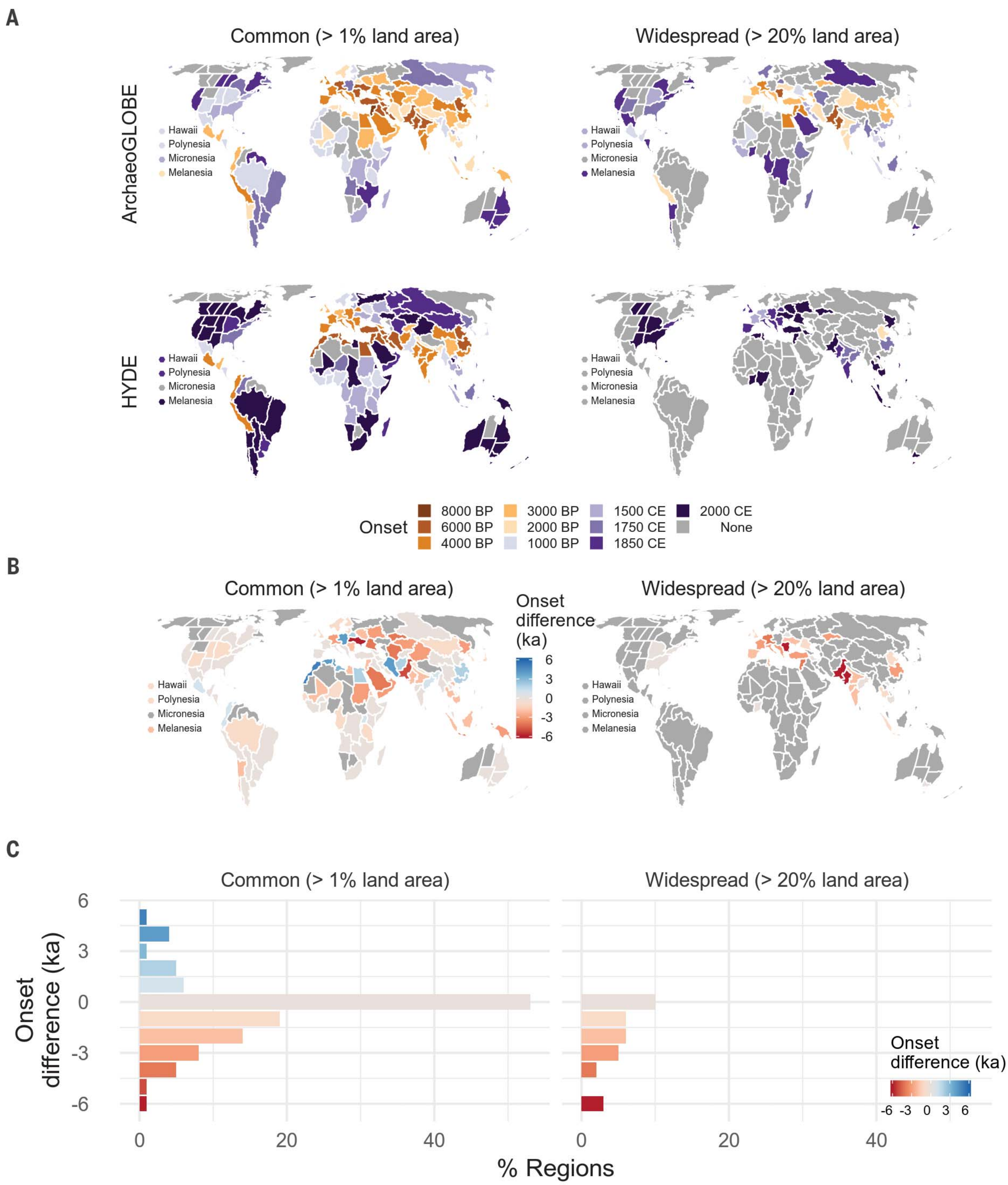

Fig. 5. Comparisons of agricultural onset in ArchaeoGLOBE versus HYDE. (**A**) Onset of intensive agriculture covering ≥1% regional area (common level) and ≥20% regional area (widespread level) in both the ArchaeoGLOBE and HYDE datasets; regions colored in gray did not surpass the associated threshold by 1850 CE for ArchaeoGLOBE and by 2000 CE for HYDE. (**B**) Map of differences in onset of intensive agriculture at common and widespread levels (in thousands of years; negative numbers highlight earlier ArchaeoGLOBE estimates). (**C**) Distributions of onset timing differences at common and widespread levels, same data and scale as (B).

patchwork of different peoples or seasonal shifts. The environmental effects of such mixed-mode land use are difficult to see in the archaeological and paleoecological record and are perhaps often missed in the dichotomous view of replacement by more advanced systems. Through time, as land became increasingly densely occupied and land use more intensive, opportunities for flexibility in subsistence strategies and the resilience that this supported were reduced.

This global archaeological assessment of early land use reveals a much earlier and more widespread global onset of intensive agriculture than the spatially explicit global historical reconstruction most commonly used to inform modeling studies of preindustrial vegetation and climate change [HYDE; (*14*)]. However, archaeological onsets of intensive agriculture appeared slightly later than those reported in the less widely used KK10 reconstruction (*15*). Substantial methodological differences and uncertainties between archaeological estimates and historical reconstructions mean that comparisons among ArchaeoGLOBE, HYDE, and KK10 must be treated with caution (*52*). The regional land-use estimates of our study represent a first step toward more accurate, empirically grounded, spatially explicit global reconstructions of long-term changes in land use and provide reference points and procedural approaches to constrain and correct these biases in future work. Our hope is that our global archaeological assessment, and the collaborative approach that it represents, will help to stimulate and support future efforts, such as work currently in progress through the PAGES LandCover6k initiative (*18*, *25*), toward the common goal of understanding early land use as a driver of long-term global environmental changes across the Earth system, including changes in climate.

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ACKNOWLEDGMENTS

Funding: This material is based upon work supported by the National Science Foundation under grant no. CNS 1125210 awarded to E.C.E. in 2011. The full list of author, affiliations, and contributions is in the supplementary materials. **Author contributions**: L.S. led the project team and designed the research. E.E. conceived of and designed the research. D.F., N.B., T.R., N.G., A.K., B.M., C.M.B., J.D.R., J.H., and E.B. assisted with research design. L.S., D.F., N.B., T.R., N.G., A.K., B.M., C.G.D.A., C.M.B., T.D., K.D., J.D., L.J., P.R., J.D.R., H.T., M.A., A.L.J., M.M.S.V., M.A., S.A., G.A., M.T.B., T.B., F.B., T.B., P.I.B., N.G.J.C., J.M.C., A.D.C., C.C., M.N.C., J.C., P.R.C., R.A.C., M.C., A.C., L.D., S.D.L., J.F.D., W.E.D., K.J.E., J.M.E., D.E., E.F., P.F., G.F., R.F., S.M.F., R.F., E.G., S.G., R.C.G., J.D.G., J.H., P.H., P.H., K.A.H., C.H., J.W.I., A.J., J.G.K., B.K., C.K., T.R.K., F.L., D.L., G-A.L., M.J.L., H.B.L., J.A.L-S., S.M., R.M., J.M.M., S.M., M.D.M., A.V.M., M.M., G.M.M., J.M., A.N., S.N., T.M.P., C.E.P., L.P., A.R.R., S.R., G.R.S., K.R., R.S., V.S., P.S., P.S., O.S., I.A.S., A.S., R.J.S., R.N.S., M.L.S., M.J.S., K.M.S., J.T., T.L.T., S.U. M.C.U., M.H.W., C.W., P.R.W., D.K.W., N.W., M.Z., and A.Z., contributed and interpreted data. J.O.K., M-J.G., and K.K.G. interpreted data. L.S., N.G., B.M., M.A., S.M.G., J.P., A.T., and E.E. conducted data analysis. L.S., D.F., N.B., T.R., N.G., A.K., B.M., C.G.D.A., T.D., K.D., J.D., L.J., P.R., J.D.R., H.T., A.L.J., M.M.S.V., J.O.K., M-J.G., K.K.G., and E.E. drafted the article. **Competing interests**: The authors declare no competing interests. **Data and materials availability**: All project data are in the public domain (CC-0) and available at Harvard Dataverse (*53*–*55*).

SUPPLEMENTARY MATERIALS

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22 February 2019; accepted 29 July 2019
10.1126/science.aax1192

Science

Archaeological assessment reveals Earth's early transformation through land use

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Science **365** (6456), 897-902.
DOI: 10.1126/science.aax1192

A synthetic history of human land use

Humans began to leave lasting impacts on Earth's surface starting 10,000 to 8000 years ago. Through a synthetic collaboration with archaeologists around the globe, Stephens *et al.* compiled a comprehensive picture of the trajectory of human land use worldwide during the Holocene (see the Perspective by Roberts). Hunter-gatherers, farmers, and pastoralists transformed the face of Earth earlier and to a greater extent than has been widely appreciated, a transformation that was essentially global by 3000 years before the present.

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Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005.