only a limited number of standard bet sizes, depending on the situation. During actual play, if the opponent bet is close enough to a standard bet size, action translation can be used to apply the blueprint strategy directly. Otherwise, Pluribus uses a real-time search, based on the actual bet size. These and other enhancements make Pluribus very computationally efficient.

The authors tested Pluribus in a series of matches. It played both against five professional human players and with one human against five Pluribus copies. Pluribus achieved superhuman performance in both cases. It plays in a style that is generally consistent with human preferences; nevertheless, just as the AI programs Chinook, TD-Gammon, and AlphaGo Zero led to a reexamining of accepted opening moves and replies, Pluribus may also challenge certain traditional beliefs about poker strategy.

Many challenges remain in the area of game learning. One target is the card game bridge, which has a larger number of game positions. Real-time strategy (RTS) games such as StarCraft (*9*) require continuous actions, and hidden information often grows as the game progresses. Coordination with teammates is a factor in some RTS games like Dota (*10*), and RoboCup Soccer, which also involves physical embodiment. Nimble adaptation to exploit the weaknesses of its opponents is another challenging area for an AI player that has only been explored to a limited degree for complex games. Algorithms like CFR have recently been applied to security games (*11*), potentially allowing methods such as those developed by Brown and Sandholm to tackle real-world problems, including infrastructure and environmental resource protection (*12*). ■

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ENVIRONMENTAL SCIENCE

How humans changed the face of Earth

Archaeological evidence shows that anthropogenic changes began earlier and spread faster than previously estimated

By **Neil Roberts**[1,2]

Scientists across disciplines have been debating potential dates for the beginning of the Anthropocene—the period during which human activity has become a dominant influence on climate change and the global environment (*1*, *2*). Recorded history has provided information with which to chart Earth's environmental changes during recent centuries. But how can it be determined if and when human activities transformed Earth during the time before written records? This question is prompted in part by the hypothesis that prehistoric deforestation and rice farming might explain the preindustrial upturn in atmospheric methane and carbon dioxide concentrations after ~7000 years ago (*3*). On page 897 of this issue, Stephens *et al.* (*4*) describe efforts by the ArchaeoGLOBE Project to crowdsource information from the global archaeological community, synthesize the data, and generate semiquantitative estimates of how various types of land use have altered Earth during the past ten millennia.

For much of the past millennium, scientists have used documentary records to reconstruct historical changes in Earth's land cover. For example, information in William the Conqueror's Domesday Survey (*5*) showed that only 15% of the surveyed land was still forested in 1086 CE; evidently, much of England's primeval wildwood had already been cleared by medieval times. Further back in time, documentary sources dry up, forcing scientists to turn to other "proxy" data sources, such as archaeology and paleoecology. Archaeological data have long been recognized as a vital source of evidence, but until recently, scaling up the data to reconstruct global trends and patterns has been done only qualitatively and incompletely.

The work by Stephens *et al.* concludes that Earth had already been substantially transformed by human activities as early as 3000 years ago. This time point for anthropogenic changes in land cover fits with several other lines of evidence (for example, reconstructions of forest loss in temperate Europe) (*6*, *7*) and broadly supports the hypothesis of Ruddiman *et al.* (*3*). On the other hand, the conclusions of Stephens *et al.* stand in contrast to the limited amount of prehistoric change reconstructed by the widely used History Database of the Global Environment (HYDE) model, which simulates past global land cover (*8*). In light of the ArchaeoGLOBE synthesis, low-end estimates for early human impact, such as in the HYDE model, become less tenable.

By the time humans abandoned this archaeological site (Mycenae, Greece) ~3000 years ago, they had already substantially transformed Earth's land surface.

The ArchaeoGLOBE synthesis is by no means the last word in the story, and by its very nature, archaeological evidence carries a number of inherent biases. In particular, archaeological data come from places inhabited by people, especially farmers (the Ecumene), rather than from parts of Earth's surface where few or no humans lived—what might today be called "wilderness areas." The ArchaeoGLOBE results, therefore, say more about the villages, fields, and paths where the proverbial Goldilocks safely lived, but much less about the surrounding wildwood inhabited by wolves and bears, and almost nothing about remote high mountains or polar deserts. Thus, it is perhaps unsurprising that Stephens *et al.* conclude that human transformation of Earth's land surface occurred at an early date.

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PHOTO: FUNKYFOOD LONDON/PAUL WILLIAMS/ALAMY STOCK PHOTO

Other empirical datasets exist that are free of this bias (for example, pollen, insect, and other paleoecological evidence); an obvious next step is to conduct a systematic comparison of these paleodata, archaeological datasets, and modeled simulations. Comparisons of regions with long histories of farming and pastoralism (such as Europe and China) over the past six millennia should show similar overall trajectories for land-cover change regardless of which data source is used, but this is clearly not the case for most regions (see the figure). In temperate Europe and northeastern China, the HYDE model shows an exponential increase in agricultural and grazing land after ~1000 years ago. By contrast, the ArchaeoGLOBE results for these regions show substantial human land conversion prior to 3000 years ago, whereas the curve for the proportion of open land according to pollen-based estimates lies somewhere in between the other two. A similar contrast is evident at a global scale, for which pollen data are not yet available. Only in Europe's boreal forest zone do temporal trends look similar regardless of the method used (see the figure). The Past Global Changes LandCover6k program is currently performing systematic intercomparison among the three data sources (*9*). These efforts must be harmonized with those of the ArchaeoGLOBE community to achieve truly multiproxy reconstructions of past land-cover changes.

The impressive results of collaborative "big data" analyses by the ArchaeoGLOBE team indicate that human transformation of Earth's land surface began well before the testing of the first atomic bomb, invention of the steam engine, or other proposed markers for the onset of the Anthropocene (*1*, *2*). A recent report from the Intergovernmental Panel on Climate Change (IPCC) (*10*) makes clear that better land management has a key role to play in keeping global warming to below 2°C. For this to occur, it is essential to take a long-term view on carbon release and the changing use of land. The ArchaeoGLOBE results should aid scientists in this endeavor. ■

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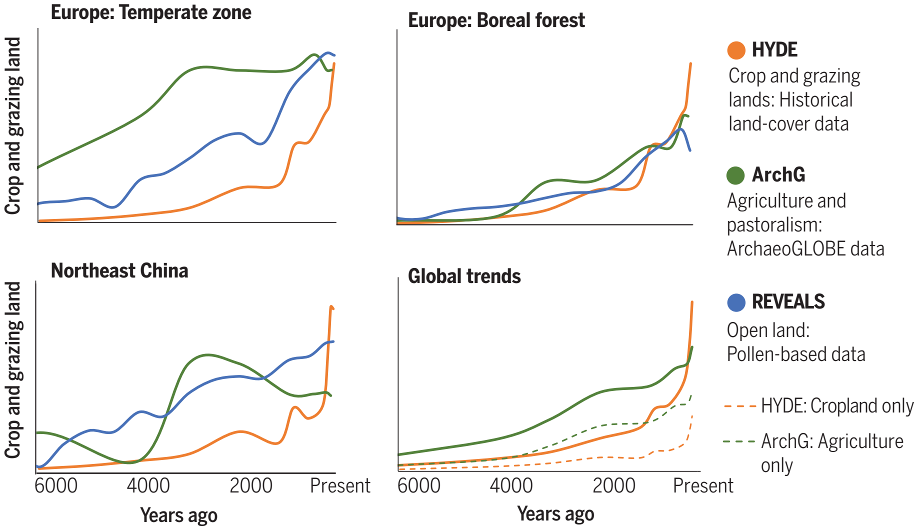
Human-driven changes in Earth's land cover

Reconstructions of the extent of agricultural and pasture land based on archaeological, modeled, and pollen data show agreement in some regions but differ widely in others. Changes after 1850 CE are not shown.



Units of measurement differ among the methods; for simplification, the graphs show indicative trends on the *y* axis. History Database of the Global Environment (HYDE) simulations in million hectares (for all of Europe and all of China), from (*8*); pollen-based Regional Estimates of Vegetation Abundance from Large Sites (REVEALS) estimates are percentage of total land area, from (*11*, *12*); ArchaeoGLOBE (ArchG) data are minimum percentage areas, from (*4*). Global HYDE data for cropland (dashed orange) and ArchG data for all agriculture (dashed green) are shown separately and combined with grazing land.

GRAPHIC: N. CARY/SCIENCE

CATALYSIS

The Mitsunobu reaction, reimagined

Catalytic nucleophilic substitution of alcohols makes organic synthesis greener

By **Lars Longwitz** *and* **Thomas Werner**

Nucleophilic substitution reactions are widely used to create carbon–heteroatom and carbon–carbon bonds as part of the synthesis of natural products and other organic molecules. These reactions typically involve a pronucleophile (NuH) and an electrophile that bears a suitable leaving group. Alcohols are often used as electrophiles because they are inexpensive and readily available. During the direct nucleophilic substitution between an alcohol and a pronucleophile, the alcohol's hydroxyl group would be replaced with the nucleophile, forming water as the sole byproduct. In the case of chiral secondary alcohols, the bimolecular substitution would lead to the substituted product with inverted stereochemistry. However, alcohols usually do not react with pronucleophiles without being activated prior to the substitution. On page 910 of this issue, Beddoe *et al.* (*1*) report an easily accessible catalyst that facilitates the direct nucleophilic substitution.

The authors' work is based on the Mitsunobu reaction, in which stoichiometric amounts of a phosphane and azodicarboxylate reagent activate the otherwise inert alcohol, promoting coupling with a wide variety of nucleophilic reaction partners (*2*, *3*). This chemistry was first reported in 1967 by Oyo Mitsunobu (*4*) and has since become a powerful synthetic tool. However, the need for stoichiometric quantitites of hazardous reagents leads to a substantial amount of waste, which does not comply with the main principles of green chemistry and sustainable synthesis, such as the principle of atom economy (*5*). A method using catalytic amounts of both the azo reagent and phosphane—called a fully catalytic Mitsunobu reaction system—could be a greener alternative but is difficult to achieve (*6*).

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