engineering technology and experts in genetics, law, and bioethics, as well as members of the scientific community, the public, and relevant government agencies and interest groups, to further consider these important issues, and where appropriate, recommend policies.

CONCLUSIONS. At the dawn of the recombinant DNA era, the most important lesson learned was that public trust in science ultimately begins with and requires ongoing transparency and open discussion. That lesson is amplified today with the emergence of CRISPR-Cas9 technology and the imminent prospects for genome engineering. Initiating these fascinating and challenging discussions now will optimize the decisions society will make at the advent of a new era in biology and genetics. ■

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GEOLOGY

Defining the epoch we live in

Is a formally designated "Anthropocene" a good idea?

By **William F. Ruddiman,[1] Erle C. Ellis,[2] Jed O. Kaplan,[3] Dorian Q. Fuller[4]**

Human alterations of Earth's environments are pervasive. Visible changes include the built environment, conversion of forests and grasslands to agriculture, algal blooms, smog, and the siltation of dams and estuaries. Less obvious transformations include increases in ozone, carbon dioxide (CO_2), and methane (CH_4) in the atmosphere, and ocean acidification. Motivated by the pervasiveness of these alterations, Crutzen and Stoermer argued in 2000 that we live in the "Anthropocene," a time in which humans have replaced nature as the dominant environmental force on Earth (*1*). Many of these wide-ranging changes first emerged during the past 200 years and accelerated rapidly in the 20th century (*2*). Yet, a focus on the most recent changes risks overlooking pervasive human transformations of Earth's surface for thousands of years, with profound effects on the atmosphere, climate, and biodiversity.

Crutzen and Stoermer originally favored placing the start of the Anthropocene in the late 1700s because of the industrial revolution initiated by James Watt's invention of the steam engine at that time. However, this choice lacked a key requirement for formal stratigraphic designation: a "golden spike" marker that is widely detectable in geologic records. Recently, a working group of the subcommission of Quaternary Stratigraphy of the Geological Society of London released a preliminary recommendation to mark the start of the Anthropocene on 16 July 1945, when the first atomic bomb test took place in Alamogordo, New Mexico (*3*). The working group chose that time because the isotopic by-products of bomb testing provide a distinctive marker horizon in ice cores, ocean and lake sediments, and soils.

This "stratigraphically optimal" choice [as it was called in (*3*)] faces intense scrutiny from scientists studying the long history of large and profound human effects on this planet (see the figure). For example, about 65% of the genera of large mammals became extinct between 50,000 and 12,500 years ago, with the two most abrupt extinction episodes in Australia and the Americas (*4*). Climate cannot be the major factor in these episodes because most of these genera had survived some 50 previous glacial-interglacial cycles. Hunting and burning by recently arrived humans is the most plausible explanation of these dramatic and unprecedented collapses.

With the beginning of the Holocene around 11,600 years ago, an even more profound human alteration of Earth's surface had begun: the Neolithic agricultural revolution (see the figure). Subsequent millennia saw global-scale changes that include domestication of the world's crops after 11,000 years ago and livestock after 9000 years ago, followed by the spread of agriculture across all of Earth's arable lands (*5*), clearance of forested regions with resulting carbon dioxide emissions after 7000 years ago (*6*), and the spread of methane-emitting rice agriculture and livestock after 5000 years ago (*7*). Reversals of a natural downward trend in atmospheric carbon dioxide after 7000 years ago and methane after 5000 years ago have both been attributed to gas emissions from farming (*8*). Other early changes include the transformation of Earth's natural biome vegetation to "anthromes" modified by human activities, with increasing habitat fragmentation (*9*); disturbance and erosion of soils by human activity (*10*, *11*); the onset of the Bronze Age 5000 years ago and of the Iron Age 3000 years ago; and the appearance of urban areas in Mesopotamia by 5000 years ago. Although these changes began slowly and at different times in different regions,

> ***"Does it really make sense to define the start of a human-dominated era millennia after most forests in arable regions had been cut for agriculture...?"***

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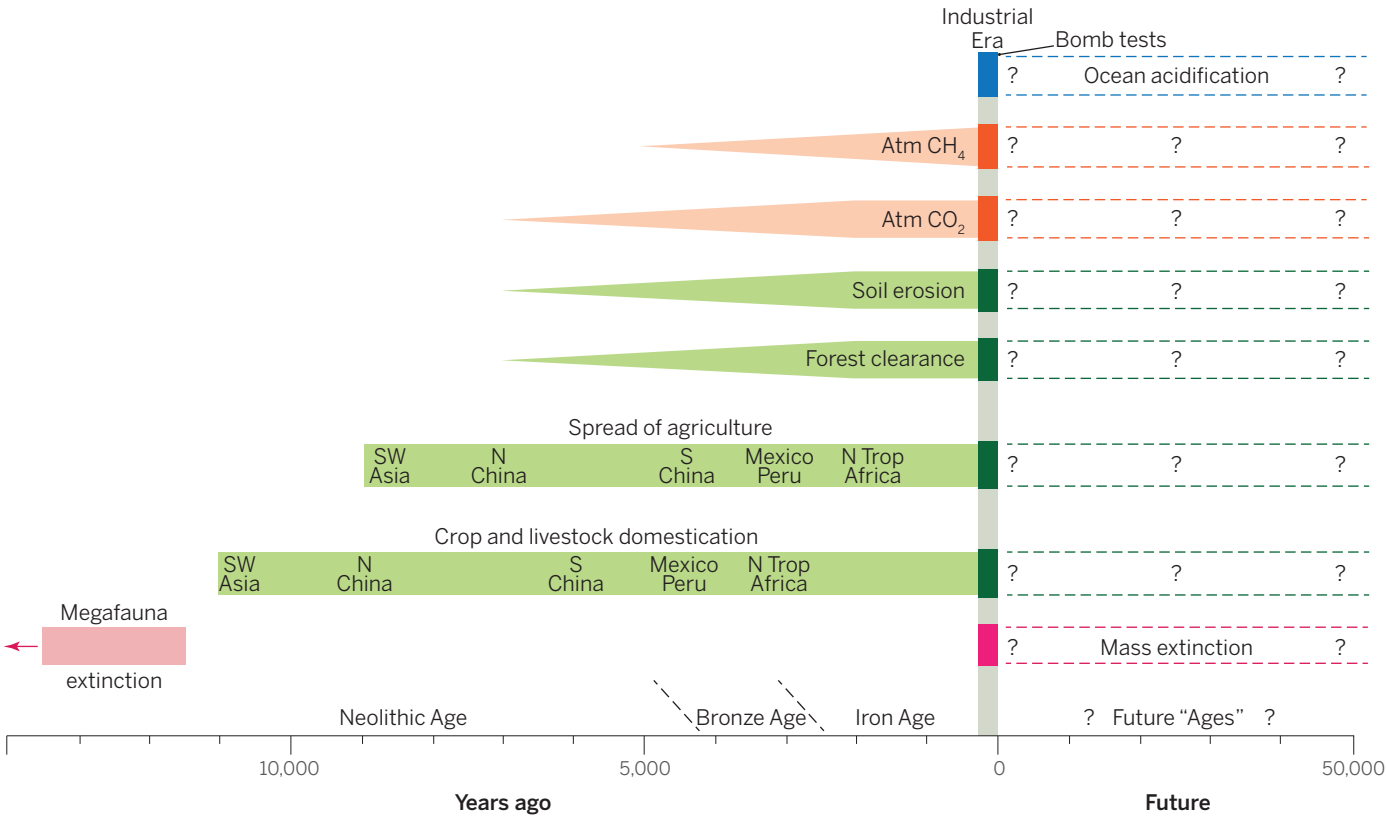
Long-term anthropogenic changes



What's in a name? The industrial era has been a time of greatly accelerated environmental changes (*1*, *2*), but it was preceded by large and important transformations, including massive large-mammal extinctions in the Americas and major changes associated with the spread of agriculture, including the spread of domesticated crops and livestock (*5*), land clearance, forest cutting, habitat transformations (*6*, *9*), irrigated rice paddies (*7*), soil erosion (*10*, *11*), and anthropogenic emissions of CO_2 and CH_4 to the atmosphere (*8*). These anthropogenic changes would not be included if the "Anthropocene" is defined by the first atomic bomb test in 1945 (*3*). Future changes, e.g., in species extinctions and ocean acidification, are projected to be much larger than those already seen, but are difficult to predict.

all reached globally significant levels millennia before the industrial era (*12*). But the timing of these changes varied from region to region, leaving no single "golden spike" to mark their onset.

Large-scale alterations of Earth's surface continued into the industrial era. Following the introduction of mechanized agriculture, most prairie and steppe grasslands had been plowed and planted with crops by 1900. Burning of fossil fuels pushed CO_2 values rapidly higher, and emissions from irrigated rice, livestock, coal mining, and landfills boosted methane levels. Two world wars introduced many new environmental upheavals, including exponential increases of lead and sulfate loadings in the atmosphere. Contrary to this increasing trend of exploitation of planet Earth, however, high northern latitude areas of Canada, the eastern United States, northern Europe, and Russia reversed millennia-long deforestation trends and began to reforest during the 1800s and 1900s as new agricultural technologies increased land-use efficiency.

Selecting 1945 as the start of the "Anthropocene" would implicitly omit these extensive agricultural and early-industrial alterations. Does it really make sense to define the start of a human-dominated era millennia after most forests in arable regions had been cut for agriculture, most rice paddies had been irrigated, and CO_2 and CH_4 concentrations had been rising because of agricultural and industrial emissions? And does it make sense to choose a time almost a century after most of Earth's prairie and steppe grasslands had been plowed and planted? Together, forest cutting and grassland conversion are by far the two largest spatial transformations of Earth's surface in human history. From this viewpoint, the "stratigraphically optimal" choice of 1945 as the start of the Anthropocene does not qualify as "environmentally optimal."

Despite differing views, the term "Anthropocene" is clearly here to stay. One way forward would be to use the term informally (with a small "a"). This approach would allow for modifiers appropriate to the specific interval under discussion, such as early agricultural or industrial. In this way, we could avoid the confinement imposed by a single formal designation, yet acknowledge the long and rich history of humanity's environmental transformations of this planet, both for better and for worse. ■

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