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Defining the Anthropocene

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Time is divided by geologists according to marked shifts in Earth's state. Recent global environmental changes suggest that Earth may have entered a new human–dominated geological epoch, the Anthropocene. Here we review the historical genesis of the idea and assess anthropogenic signatures in the geological record against the formal requirements for the recognition of a new epoch. The evidence suggests that of the various proposed dates two do appear to conform to the criteria to mark the beginning of the Anthropocene: 1610 and 1964. The formal establishment of an Anthropocene Epoch would mark a fundamental change in the relationship between humans and the Earth system.

Human activity has been a geologically recent, yet profound, influence on the global environment. The magnitude, variety and longevity of human-induced changes, including land surface transformation and changing the composition of the atmosphere, has led to the suggestion that we should refer to the present, not as within the Holocene Epoch (as it is currently formally referred to), but instead as within the Anthropocene Epoch[1–4] (Fig. 1). Academic and popular usage of the term has rapidly escalated[5,6] following two influential papers published just over a decade ago[1,2]. Three scientific journals focusing on the topic have launched: *The Anthropocene*, *The Anthropocene Review* and *Elementa*. The case for a new epoch appears reasonable: what matters when dividing geological-scale time is global-scale changes to Earth's status, driven by causes as varied as meteor strikes, the movement of continents and sustained volcanic eruptions. Human activity is now global and is the dominant cause of most contemporary environmental change. The impacts of human activity will probably be observable in the geological stratigraphic record for millions of years into the future[7], which suggests that a new epoch has begun[4].

Nevertheless, some question the types of evidence[8,9], because to define a geological time unit, formal criteria must be met[10,11]. Global-scale changes must be recorded in geological stratigraphic material, such as rock, glacier ice or marine sediments (see Box 1). At present, there is no formal agreement on when the Anthropocene began, with proposed dates ranging from before the end of the last glaciation to the 1960s. Such different meanings may lead to misunderstandings and confusion across several disciplines. Furthermore, unlike other geological time unit designations, definitions will probably have effects beyond geology. For example, defining an early start date may, in political terms, 'normalize' global environmental change. Meanwhile, agreeing a later start date related to the Industrial Revolution may, for example, be used to assign historical responsibility for carbon dioxide emissions to particular countries or regions during the industrial era. More broadly, the formal definition of the Anthropocene makes scientists arbiters, to an extent, of the human–environment relationship, itself an act with consequences beyond geology. Hence, there is more interest in the Anthropocene than other epoch definitions. Nevertheless, evidence will define whether the geological community formally ratifies a human-activity-induced geological time unit.

We therefore review human geology in four parts. First, we summarize the geologically important human-induced environmental impacts. Second, we review the history of naming the epoch that modern human societies live within, to provide insights into contemporary Anthropocene-related debates. Third, we assess environmental changes caused by human activity that may have left global geological markers consistent with the formal criteria that define geological epochs. Fourth, we highlight the

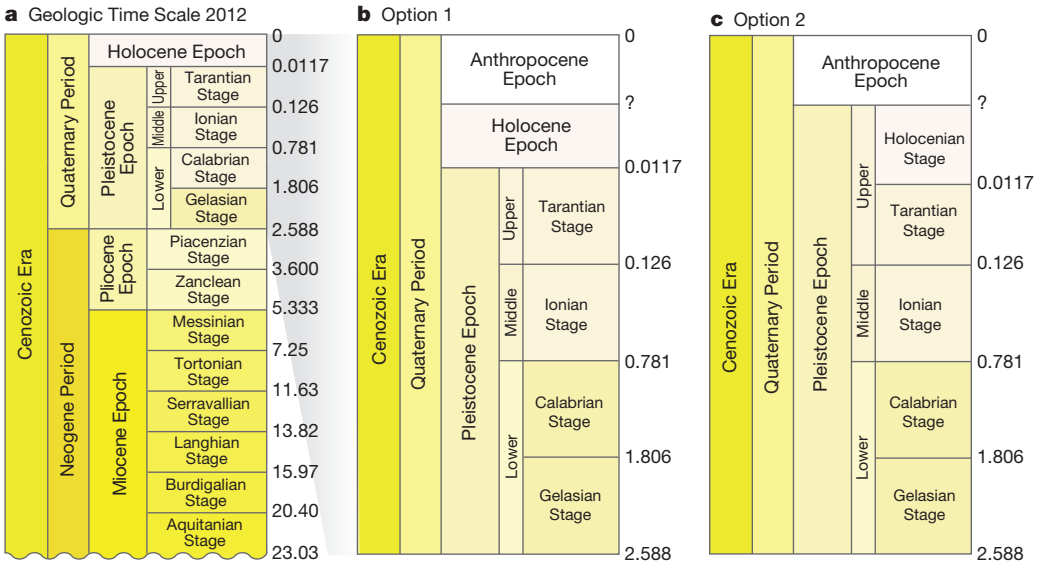

Figure 1 | Comparison of the current Geologic Time Scale[10] (GTS2012), with two alternatives. **a**, GTS2012, with boundaries marked in millions of years (ref. 10). **b**, **c**, The alternatives include a defined Anthropocene Epoch following either the Holocene (**b**) or directly following the Pleistocene (**c**). Defining the Anthropocene as an epoch requires a decision as to whether the Holocene is as distinct as the Anthropocene and Pleistocene; retaining it or not distinguishes between **b** and **c**. The question mark represents the current debate over the start of the Anthropocene, assuming it is formally accepted as an epoch (see Box 1, Fig. 2). Colour coding is used according to the Commission for the Geological Map of the World[10], except for the Anthropocene.

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BOX 1

Dividing geological time

Geological time is divided into a hierarchical series of ever-finer units (Fig. 1a). The present, according to *The Geologic Time Scale 2012*[10], is in the Holocene Epoch (Greek for 'entirely recent'; started 11,650 yr BP), within the Quaternary Period (started 2.588 million years ago), within the Cenozoic Era ('recent life'; started 66 million years ago) of the Phanerozoic Eon ('revealed life'; started 541 million years ago). Divisions represent differences in the functioning of Earth as a system and the concomitant changes in the resident life-forms. Larger differences result in classifications at higher unit-levels.

Formally, geological time units are defined by their lower boundary, that is, their beginning. Boundaries are demarcated using a GSSP, or if good candidate GSSPs do not exist, by an agreed date, termed a GSSA[10]. For a GSSP, a 'stratotype section' refers to a portion of material that develops over time (rock, sediment, glacier ice), and 'point' refers to the location of the marker within the stratotype. Each 'golden spike' is a single physical manifestation of a change recorded in a stratigraphic section, often reflecting a global-change phenomenon. GSSP markers are then complemented by a series of correlated changes, also recorded stratigraphically, termed auxiliary stratotypes, indicating widespread changes to the Earth system occurring at that time[10]. An exemplary GSSP is the Cretaceous–Paleogene period-level boundary, and the start of the Cenozoic Era, when non-avian dinosaurs declined to extinction and mammals radically increased in variety and abundance. The GSSP boundary marker is the peak in iridium—a residual of bolide impact with Earth—in rock dated at 66 million years ago, located at El Kef, Tunisia[10].

The widespread appearance of new species can also be used as GSSP boundary markers; for example, the Ordovician–Silurian period-level boundary, 443.8 million years ago, is marked by the appearance of a distinct planktonic graptolite, *Akidograptus ascensus* (a now-extinct hemichordate)[10]. From an Anthropocene perspective this example shows that the GSSP primary marker chosen as a boundary indicator may be of limited importance compared to the other events taking place that collectively show major changes to Earth at that time[67].

Formally, a GSSP must have (1) a principal correlation event (the marker), (2) other secondary markers (auxiliary stratotypes), (3) demonstrated regional and global correlation, (4) complete continuous sedimentation with adequate thickness above and below the marker, (5) an exact location—latitude, longitude and height/depth—because a GSSP can be located at only one place on Earth, (6) be accessible, and (7) have provisions for GSSP conservation and protection[10].

Alternatively, following a survey of the stratigraphic evidence, a GSSA date may be agreed by committee to mark a time unit boundary. GSSAs are typical in the Precambrian (>541 million years ago) because well-defined geological markers and clear events are less obvious further back in time[10]. Regardless of the marker type, formally ratifying a new Anthropocene Epoch into the GTS would first require a positive recommendation from the Anthropocene Working Group of the Subcommission of Quaternary Stratigraphy, followed by a supermajority vote of the International Commission on Stratigraphy, and finally ratification by the International Union of Geological Sciences[10] (see ref. 11 for full details).

advantages and disadvantages of the few global markers that may indicate a date to define the beginning of the Anthropocene. By consolidating research from disparate fields and the emerging Anthropocene-specific literature we aim to constrain the number of possible Anthropocene start dates, highlight areas requiring further research, and assist in moving towards an evidence-based decision on the possible ratification of a new Anthropocene Epoch.

The geological importance of human actions

Human activity profoundly affects the environment, from Earth's major biogeochemical cycles to the evolution of life. For example, the early-twentieth-century invention of the Haber–Bosch process, which allows the conversion of atmospheric nitrogen to ammonia for use as fertilizer, has altered the global nitrogen cycle so fundamentally that the nearest suggested geological comparison refers to events about 2.5 billion years ago[12]. Human actions have released 555 petagrams of carbon (where 1 Pg = 10^{15} g = 1 billion metric tons) to the atmosphere since 1750, increasing atmospheric CO_2 to a level not seen for at least 800,000 years, and possibly several million years[13,14], thereby delaying Earth's next glaciation event[15]. The released carbon has increased ocean water acidity at a rate probably not exceeded in the last 300 million years[16].

Human action also affects non-human life. Global net primary productivity appears to be relatively constant[17]; however, the appropriation of 25–38% of net primary productivity for human use[17,18] reduces the amount available for millions of other species on Earth. This land-use conversion to produce food, fuel, fibre and fodder, combined with targeted hunting and harvesting, has resulted in species extinctions some 100 to 1,000 times higher than background rates[19], and probably constitutes the beginning of the sixth mass extinction in Earth's history[19]. Species removals are non-random, with greater losses of large-bodied species from both the land and the oceans. Organisms have been transported around the world, including crops, domesticated animals and pathogens on land. Similarly, boats have transferred organisms among once-disconnected oceans. Such movement has led to a small number of extraordinarily common species, new hybrid species[20], and a global homogenization of Earth's biota. Ostensibly, this change is unique since Pangaea separated about 200 million years ago[21], but such trans-oceanic exchanges probably have no geological analogue.

Furthermore, human actions may well constitute Earth's most important evolutionary pressure[22,23]. The development of diverse products, including antibiotics[22], pesticides[22,24], and novel genetically engineered organisms[24], alongside the movement of species to new habitats[25], intense harvesting[23] and the selective pressure of higher air temperatures resulting from greenhouse gas emissions, are all likely to alter evolutionary outcomes[22–25]. Considered collectively, there is no geological analogue[22]. Furthermore, given that the lifespan of a species is typically 1–10 million years, the rates of anthropogenic environmental change in the near future may exceed the rates of change encountered by many species in their evolutionary history. Human activity has clearly altered the land surface, oceans and atmosphere, and re-ordered life on Earth.

Historical human geology

Human-related geological time units have a long history[26]. In 1778 Buffon published an early attempt to describe Earth's history, allocating a human epoch to be Earth's seventh and final epoch, paralleling the seven-day creation story[27]. By the nineteenth century, divine intervention was receding from consideration as a geological force. In 1854 the Welsh geologist and professor of theology, Thomas Jenkyn, appears to have first published the idea of an explicitly evidence-based human geological time unit in a series of widely disseminated geology lessons[28–30]. He describes the then present day as "the human epoch" based on the likely future fossil record[28]. In his final lecture he wrote, "All the recent rocks, called in our last lesson Post-Pleistocene, might have been called Anthropozoic, that is, human-life rocks."[29]. Similarly, the Reverend Haughton's 1865 Manual of Geology describes the Anthropozoic as the "epoch in which we live"[31], as did the Italian priest and geologist Antonio Stoppani a decade later[32]. Meanwhile in the USA, the geology professor James Dwight Dana's then-popular 1863 Manual of Geology[33] extensively refers to the "Age of Mind and Era of Man" as the youngest geological time, as did many of his US contemporaries[34].

In 1830 Charles Lyell had proposed that contemporary time be termed the Recent epoch[35] on the basis of three considerations: the end of the last glaciation, the then-believed coincident emergence of humans, and the

rise of civilizations[26,35]. In the 1860s, the French geologist Paul Gervais made Lyell's term international, coining the term Holocene, derived from the Greek for 'entirely recent'. Thus, most nineteenth-century geological textbooks feature humans as part of the definition of the most recent geological time units. Critically, there was little discussion about any of these terms—Recent, Holocene or Anthropozoic—probably because each represented the same conceptual model and broad agreement that humans were part of the definition of the contemporary geological epoch. However, the wider written records of these often deeply religious men show that a separate human epoch was likely to have been more strongly influenced by theological concerns—in particular, separating *Homo sapiens* from other animals and retaining humans at the apex of life on Earth—than by the appraisal of stratigraphic evidence.

In the twentieth century, geologists in the West increasingly used the term Holocene for the current epoch, and Quaternary for the period. Meanwhile, in 1922 the Russian geologist Aleksei Pavlov described the present day as part of an "Anthropogenic system (period) or Anthropocene"[36]. The Ukrainian geochemist Vladimir Vernadsky then brought to widespread attention the idea that the biosphere, combined with human cognition, had created the Noösphere (from the Greek for mind), with humans becoming a geological force[37]. The term Noösphere was not well used, but non-Western scientists often used anthropogenic geological time units. The Russian term was anglicized as both Anthropogene and Anthropocene[36], sometimes creating confusion. The East–West differences in usage may have been due to differing political ideologies: an orthodox Marxist view of the inevitability of global collective human agency transforming the world politically and economically requires only a modest conceptual leap to collective human agency as a driver of environmental transformation. Again there was little broad interest in the various terms. The Holocene became the official term within the Geologic Time Scale (GTS; Fig. 1)[10,38], with its implication that the current interglacial differs from the previous Pleistocene interglacials owing to the influence of humans. It has therefore been argued that an Anthropocene Epoch is not required, given that some human influence is already contained within the definition of the Holocene Epoch[9]. Alternatively, defining the Anthropocene would deprive the Holocene Epoch of its ostensibly unique feature—humans—suggesting that the Holocene as an epoch may not be required.

The views of nineteenth- and twentieth-century scientists illustrate the influence of the dominant contemporary concerns on geological debates. Today's scientists may also not be immune to such influences. For example, a key concern for scientists and others is the central role of technology in modern society and its environmental impacts. Crutzen and Stoermer[1] originally proposed that the start of the Anthropocene should be coincident with the beginning of the Industrial Revolution and James Watt's 1784 refinement of the steam engine. Others followed, including stratigraphers, suggesting that 1800 should be the beginning of the Anthropocene[39,40], despite a lack of corresponding global geological markers, and the presence of well-known stratigraphic evidence suggestive of different dates, such as the radionuclide fallout from mid-twentieth-century nuclear weapons tests. Care is needed to ensure that the dominant culture of today's scientists does not subconsciously influence the assessment of stratigraphic evidence.

A human golden spike

Defining the beginning of the Anthropocene as a formal geologic unit of time requires the location of a global marker of an event in stratigraphic material, such as rock, sediment, or glacier ice, known as a Global Stratotype Section and Point (GSSP), plus other auxiliary stratigraphic markers indicating changes to the Earth system. Alternatively, after a survey of the stratigraphic evidence, a date can be agreed by committee, known as a Global Standard Stratigraphic Age (GSSA). GSSPs, known as 'golden spikes', are the preferred boundary markers[10] (see Box 1).

Generally, geologists have used temporally distant changes in multiple stratigraphic records to delimit major changes in the Earth system and thereby geological time units, for example, the appearance of new species as fossils within rocks, coupled with other temporally coincident changes. Perhaps the most useful GSSP example when considering a possible Anthropocene GSSP is that marking the beginning of the most recent epoch, the Holocene[38], because some similar choices and difficulties were faced. These include: not relying on solid aggregate mineral deposits ('rock') for the boundary; an event horizon largely lacking fossils (although fossils are used to recognize Holocene deposits); the need for very precise GSSP dating of events in the recent past; and how to formalize a time unit that extends to the present and thereby implicitly includes a view of the future.

Depending on the parameter considered, the current interglacial took decades to millennia to unfold, as global climate, atmospheric chemistry and the distribution of plant and animal species all altered. From these changes a single dated level within a single stratigraphic record was required to be chosen as a GSSP primary marker (Box 1; Fig. 2). Thus, formally, the Holocene is marked by an abrupt shift in deuterium (^{2}H) excess values at a depth of 1,492.25 m in the NorthGRIP Greenland ice core, dated 11,650 ± 99 yr BP (before present, where 'present' is defined to be 1950)[38]. This corresponds to the first signs of predominantly Northern Hemisphere climatic warming at the end of the Younger Dryas/ Greenland Stadial 1 cold period[38] (Fig. 2). Five further auxiliary stratotypes (four lakes and one marine sediment) showing clear correlated changes across the boundary complement the GSSP, consistent with the occurrence of global changes to the Earth system[38]. The requirements for a formal definition of the start of the Anthropocene are similar: a clear, datable marker documenting a global change that is recognizable in the stratigraphic record, coupled with auxiliary stratotypes documenting long-term changes to the Earth system.

Defining the Anthropocene presents a further challenge. Changes to the Earth system are not instantaneous. However, even spatially heterogeneous and diachronous (producing similar stratigraphic material varying in age) changes appear near-instantaneous when viewed millions of years after the event, especially as time-lags often fall within the error range of the dating techniques. In contrast, Anthropocene deposits are commonly dated on decadal or annual scales, so that all changes will appear diachronous, to some extent, from today's perspective (but not from far in the future)[11,41]. Judgement will be required to assess whether the time-lags following events and their significant global impacts are too long to be of use when defining any Anthropocene GSSP.

Several approaches have been put forward to define when the Anthropocene began, including those focusing on the impact of fire[42], pre-industrial farming[43–45], sociometabolism[46], and industrial technologies[1,39,40,41,47], but the relative merits of the evidence for various starting dates have not been systematically assessed against the requirements of a golden spike. Below, we review the major events in human history and pre-history and their impact on stratigraphic records. We focus on continuous stratigraphic material that may yield markers consistent with a GSSP (lake and marine sediments, glacier ice) and on the types of chemical, climatic and biological changes used to denote other epoch boundaries further in the past. We proceed chronologically forward in time, presenting the reason why each event was originally proposed, evaluate the existence of stratigraphic markers, and assess whether the event provides a potential GSSP. The hypotheses and evidence are summarized in Table 1. Following the evidence review we briefly consider the relative merits of the differing events that probably fulfil the GSSP criteria, and assess related GSSA dates.

Pleistocene human impacts

The first major impacts of early humans on their environment was probably the use of fire. Fossil charcoal captures these events from the Early Pleistocene Epoch[42,48]. However, fires are inherently local events, so they do not provide a global GSSP. The next suggested candidate is the Megafauna Extinction between 50,000 and 10,000 years ago, given that other epoch boundaries have been defined on the basis of extinctions or on the resultant newly emerging species[10]. Overall, during the Megafauna Extinction about half of all large-bodied mammals worldwide, equivalent to 4% of all mammal species, were lost[49]. The losses were not evenly distributed: Africa lost 18%, Eurasia lost 36%, North

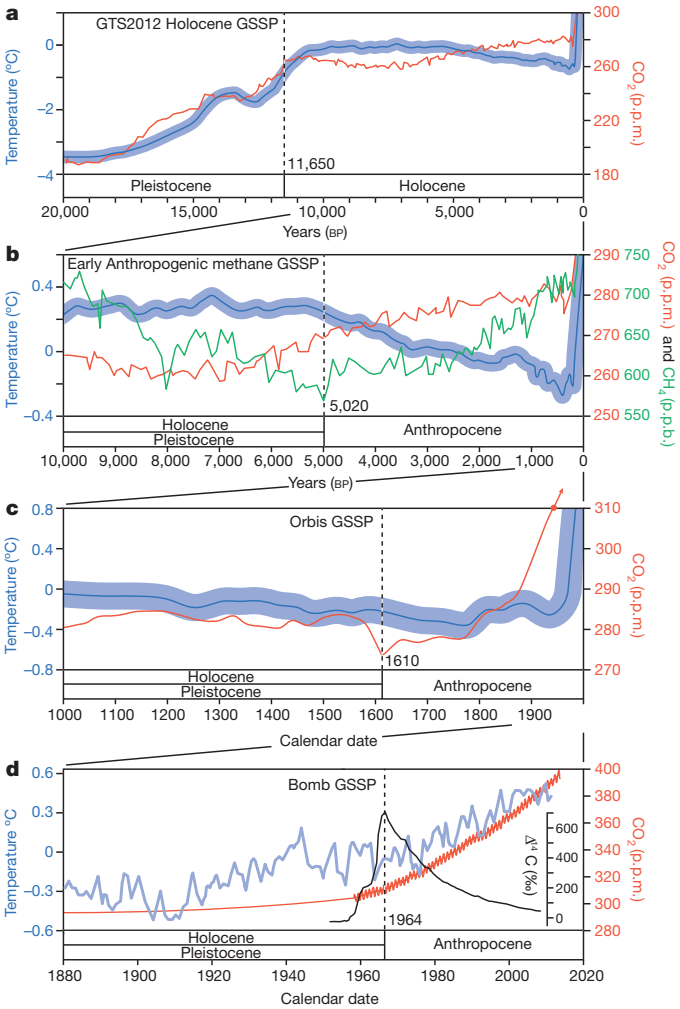

Figure 2 | Defining the beginning of the Anthropocene. **a**, Current GTS2012 GSSP boundary between the Pleistocene and Holocene[38] (dashed line), with global temperature anomalies (relative to the early Holocene average over the period 11,500 BP to 6,500 BP)[112] (blue), and atmospheric carbon dioxide composite[113] on the AICC2012 timescale[114] (red). **b**, Early Anthropogenic Hypothesis GSSP suggested boundary (dashed line), which posits that early extensive farming impacts caused global environmental changes, defined here by the inflection and lowest level of atmospheric methane (in parts per billion, p.p.b.) from the GRIP ice core[59] (green), with global temperature anomalies (relative to the average over the period 1961 to 1990)[115] (blue), and atmospheric carbon dioxide[113] (red). **c**, Orbis GSSP suggested boundary (dashed line), representing the collision of the Old and New World peoples and homogenization of once distinct biotas, and defined by the pronounced dip in atmospheric carbon dioxide (dashed line) from the Law Dome ice core[75,76] (blue), with global temperature data anomalies (relative to the average over the period 1961 to 1990)[115] (red). **d**, Bomb GSSP suggested boundary (dashed line), characterized by the peak in atmospheric radiocarbon from annual tree-rings (black)[103] (the $\Delta^{14}C$ value is the relative difference between the absolute international standard (base year 1950) and sample activity corrected for the time of collection and $\delta^{13}C$), with atmospheric carbon dioxide from Mauna Loa, Hawaii, post-1958[116], and ice core records pre-1958[75,76] (red), and global temperature anomalies (relative to the average over the period 1961 to 1990)[116] (blue).

America lost 72%, South America lost 83%, and Australia lost 88% of their large-bodied mammalian genera[50,51]. So the Megafauna Extinction was actually a series of events on differing continents at differing times and therefore lacks the required precision for an Anthropocene GSSP marker.

Origins and impacts of farming

The development of agriculture causes long-lasting anthropogenic environmental impacts as it replaces natural vegetation, and thereby increases species extinction rates, and alters biogeochemical cycles. Agriculture had multiple independent origins: first occurring about 11,000 years ago in southwest Asia, South America and north China; between 6,000–7,000 years ago in Yangtze China and Central America; and 4,000–5,000 years ago in the savanna regions of Africa, India, southeast Asia, and North America[52]. Thus, the increasing presence of fossil pollen from domesticated plants in sediment is too local and lacking in global synchrony to form a GSSP marker. Critically, for the Holocene GSSP, auxiliary markers within stratigraphic material did not include any human-derived markers[38], illustrating the lack of anthropogenic impacts at that time. Long-lasting cultural evidence related to agriculture is similarly constrained. Although ceramics are datable and preserved in stratigraphic records (for example, the mineral mullite[41]), they appeared in Africa before agriculture, while early southwest Asian farming cultures did not produce ceramics. Similarly, anthropogenically formed soils, derived from intensive farmland management, have also been suggested as a marker of the Anthropocene[53]. Although these soils are widespread, like vegetation clearance, they are highly diachronous over about 2,000 yr, thus excluding their use as a GSSP marker[54].

A series of Neolithic revolutions resulted in the majority of *Homo sapiens* becoming agriculturalists to some extent by around 8,000 yr BP, rising to a maximum of about 99% by about 500 yr BP[46]. The Early Anthropogenic Hypothesis posits that the current interglacial was similar to the previous seven interglacial periods until around 8,000 yr BP[43,55]. By comparison with the closest astronomical analogue of the current interglacial (795,000–780,000 yr BP)[55], atmospheric CO_2 should have continued to decline after 8,000 yr BP, eventually reaching about 240 parts per million (p.p.m.), and the onset of glaciation should have begun[43,55]. However, by 6,000–8,000 yr BP, farmers' conversion of high-carbon storage vegetation (forest, woodland, woody savanna) to crops and grazing lands, plus associated fire impacts, may have increased atmospheric CO_2 levels, and postponed this new glaciation[43] (Fig. 2). Thus, the lowest level of CO_2 within an ice core record could, in principle, provide a golden spike, but the CO_2 record lacks a distinct inflection point at this time (Fig. 2). Furthermore, the evidence that human activity was responsible for the gradual increase in CO_2 after 6,000 yr BP is extensively debated[43,56–58].

Methane provides a clearer inflection point, which may provide a possible GSSP at 5,020 yr BP, the date of the lowest methane value recorded in the GRIP ice core[59] (Fig. 2). Archaeological evidence suggests that the inflection is caused by rice cultivation in Asia and the expansion of populations of domesticated ruminants. Comparisons of changes in atmospheric methane from the current and past interglacials[43], and some methane $\delta^{13}C$ value evidence[60], also suggest a human cause. However, a model study suggests that orbital forcing altering methane emissions from tropical wetlands may be responsible[61]. Auxiliary markers could include stone axes and fossilized domesticated crop pollen and ruminant remains, but these do not provide temporally well-correlated markers that collectively document globally synchronous changes to the Earth system.

Collision of the Old and New Worlds

The arrival of Europeans in the Caribbean in 1492, and subsequent annexing of the Americas, led to the largest human population replacement in the past 13,000 years[62], the first global trade networks linking Europe, China, Africa and the Americas[63,64], and the resultant mixing of previously separate biotas, known as the Colombian Exchange[63,64]. One biological result of the exchange was the globalization of human foodstuffs. The New World crops maize/corn, potatoes and the tropical staple manioc/cassava were subsequently grown across Europe, Asia and Africa. Meanwhile, Old World crops such as sugarcane and wheat were planted in the New World. The cross-continental movement of dozens of other food species (such as the common bean, to the New World), domesticated animals (such as the horse, cow, goat and pig, all to the Americas) and human commensals (the black rat, to the Americas), plus accidental transfers (many species of earth worms, to North America; American mink to Europe) contributed to a swift, ongoing, radical reorganization of life on Earth without geological precedent.

Table 1 | Potential start dates for a formal Anthropocene Epoch

Event	Date	Geographical extent	Primary stratigraphic marker	Potential GSSP date*	Potential auxiliary stratotypes
Megafauna extinction	50,000–10,000 yr BP	Near-global	Fossil megafauna	None, diachronous over ~40,000 yr	Charcoal in lacustrine deposits
Origin of farming	~11,000 yr BP	Southwest Asia, becoming global	Fossil pollen or phytoliths	None, diachronous over ~5,000 yr	Fossil crop pollen, phytoliths, charcoal
Extensive farming	~8,000 yr BP to present	Eurasian event, global impact	CO_2 inflection in glacier ice	None, inflection too diffuse	Fossil crop pollen, phytoliths, charcoal, ceramic minerals
Rice production	6,500 yr BP to present	Southeast Asian event, global impact	CH_4 inflection in glacier ice	5,020 yr BP CH_4 minima	Stone axes, fossil domesticated ruminant remains
Anthropogenic soils	~3,000–500 yr BP	Local event, local impact, but widespread	Dark high organic matter soil	None, diachronous, not well preserved	Fossil crop pollen
New–Old World collision	1492–1800	Eurasian–Americas event, global impact	Low point of CO_2 in glacier ice	1610 CO_2 minima	Fossil pollen, phytoliths, charcoal, CH_4, speleothem $\delta^{18}O$, tephra†
Industrial Revolution	1760 to present	Northwest Europe event, local impact, becoming global	Fly ash from coal burning	~1900 (ref. 94); diachronous over ~200 yr	^{14}N:^{15}N ratio and diatom composition in lake sediments
Nuclear weapon detonation	1945 to present	Local events, global impact	Radionuclides (^{14}C) in tree-rings	1964 ^{14}C peak§	^{240}Pu: ^{239}Pu ratio, compounds from cement, plastic, lead and other metals
Persistent industrial chemicals	~1950 to present	Local events, global impact	For example, SF_6 peak in glacier ice	Peaks often very recent so difficult to accurately date§	Compounds from cement, plastic, lead and other metals

For compliance with a Global Stratotype Section and Point (GSSP) definition, a clearly dated global marker is required, backed by correlated auxiliary markers that collectively indicate global and other widespread and long-term changes to the Earth system. BP, before present, where present is defined as calendar date 1950.
* Requires a specific date for a GSSP primary marker. †From Huaynaputina eruption in 1600 (refs 78, 79).
§ Peak, rather than earliest date of detection selected, because earliest dates reflect available detection technology, are more likely influenced by natural background geochemical levels[101], and will be more affected by the future decay of the signal, than peak values.

In terms of stratigraphy, the appearance of New World plant species in Old World sediments—and vice versa—may provide a common marker of the Anthropocene across many deposits because pollen is often well preserved in marine and lake sediments. For example, pollen of New World native *Zea mays* (maize/corn), which preserves very well[41], first appears in a European marine sediment core in 1600[65]. The European Pollen Database lists a further 70 lake and marine sediment cores containing *Zea mays* after this date. Phytoliths can similarly record such range expansions[66]. Specifically, the transcontinental range extension of at least one Old World species into the New World (banana, as phytoliths in Central and tropical South America sediments) and a second species from the New World expanding into the Old World (maize/corn, as pollen preserved in sediments in Eurasia and Africa) together constitute a unique signature in the stratigraphic record. This transcontinental range expansion—stratigraphically marking before and after an event—is comparable to the use of the appearance of new species as boundary markers in other epoch transitions[49,67].

Besides permanently and dramatically altering the diet of almost all of humanity, the arrival of Europeans in the Americas also led to a large decline in human numbers. Regional population estimates sum to a total of 54 million people in the Americas in 1492[68], with recent population modelling estimates of 61 million people[58]. Numbers rapidly declined to a minimum of about 6 million people by 1650 via exposure to diseases carried by Europeans, plus war, enslavement and famine[58,63,68,69]. The accompanying near-cessation of farming and reduction in fire use resulted in the regeneration of over 50 million hectares of forest, woody savanna and grassland with a carbon uptake by vegetation and soils estimated at 5–40 Pg within around 100 years[58,70–72]. The approximate magnitude and timing of carbon sequestration suggest that this event significantly contributed to the observed decline in atmospheric CO_2 of 7–10 p.p.m. (1 p.p.m. CO_2 = 2.1 Pg of carbon) between 1570 and 1620 documented in two high-resolution Antarctic ice core records[73–76] (Fig. 2 and Box 2). This dip in atmospheric CO_2 is the most prominent feature, in terms of both rate of change and magnitude, in pre-industrial atmospheric CO_2 records over the past 2,000 years[75] (Fig. 2).

On the basis of the movement of species, atmospheric CO_2 decline and the resulting climate-related changes within various stratigraphic records, we propose that the 7–10 p.p.m. dip in atmospheric CO_2 to a low point of 271.8 p.p.m. at 285.2 m depth of the Law Dome ice core[75], dated 1610 (±15 yr; refs 75, 76), is an appropriate GSSP marker (Fig. 2). Auxiliary stratotypes could include: the first occurrence of a cross-ocean range extension in the fossil record (*Zea mays*, in 1600[65]) plus a range of deposits showing distinct changes at that time, including tephra[77,78] and other signatures from the 1600 Huaynaputina eruption detected at both poles and in the tropics[77–79]; charcoal reductions in deposits in the Americas[71] and globally[80]; decreases in atmospheric methane, enrichment of methane $\delta^{13}C$, and decreases in carbon monoxide in Antarctic ice cores[60,81–84]; pollen in lacustrine sediments showing vegetation regeneration[85]; proxies indicating anomalous Arctic sea-ice extent[86]; changing $\delta^{18}O$ derived from speleothems from caves in China and Peru[14] and other studies noting changes coincident with 1600 and the coolest part of the Little Ice Age (1594–1677; ref. 87), a relatively synchronous global event noted in geologic deposits worldwide[87].

The impacts of the meeting of Old and New World human populations—including the geologically unprecedented homogenization of Earth's biota[63,64]—may serve to mark the beginning of the Anthropocene. Although it represents a major event in world history[62–64,88], the collision of the Old and New Worlds has not been proposed previously, to our knowledge, as a possible GSSP. We suggest naming the dip in atmospheric CO_2 the 'Orbis spike' and the suite of changes marking 1610 as the beginning of the Anthropocene the 'Orbis hypothesis', from the Latin for world, because post-1492 humans on the two hemispheres were connected, trade became global, and some prominent social scientists refer to this time as the beginning of the modern 'world-system'[89].

Industrialization

The beginning of the Industrial Revolution has often been suggested as the beginning of the Anthropocene, because accelerating fossil fuel use and coupled rapid societal changes herald something important and unique in human history[1–4,39]. Yet humans have long been engaging in industrial-type production, such as metal utilization from around 8,000 yr BP onwards, with attendant pollution[90]. Elevated mercury records are documented at around 3,400 yr BP in the Peruvian Andes[91], while the impacts of Roman Empire copper smelting are detectable in a Greenland ice core at around 2,000 yr BP[92]. This metal pollution, like other examples predating the Industrial Revolution, is too local and diachronous to provide a golden spike.

BOX 2

Origins of the 1610 decrease in atmospheric CO_2

Is the CO_2 decline real?

Two independent high-resolution Antarctic ice core records from the Law Dome and the Western Antarctic Ice Sheet show a reduction in atmospheric CO_2 of 7–10 p.p.m. between 1570 and 1620[73–75] (Fig. 2). A smaller CO_2 decrease is also observed in less highly resolved Antarctic cores[117,118]. The decline exceeds the measurement error of the cores, 1–2 p.p.m., and experiments suggest that it does not result from *in situ* changes within the ice core[119].

Did human activity cause the decline?

The arrival of Europeans in the Americas led to a catastrophic decline in human numbers, with about 50 million deaths between 1492 and 1650, according to several independent sources[58,63,68,69]. Contemporary field observations of soil[120] and vegetation[121] carbon dynamics following agriculture abandonment suggest that about 65 million hectares (that is, 50 million people × 1.3 hectares per person) would sequester 7–14 Pg of carbon over 100 years (that is, 100–200 Mg of carbon per hectare total uptake, above- and below-ground). Reduction in fire use for land management would additionally increase carbon uptake outside farmed areas. Studies using a variety of methods report broadly consistent estimates[58,70–72] of carbon uptake by vegetation of 5–40 Pg (2.1 Pg of carbon = 1 p.p.m. atmospheric CO_2 over shorter timescales, lessening over time[127]). Given that maximum human mortality rates were not reached for some decades after 1492[62,63], and maximum carbon uptake would take place 20–50 yr after farming abandonment, peak carbon sequestration would occur approximately between 1550 and 1650.

Some model studies spanning thousands of years find a net land surface carbon uptake spanning 1500–1650 across the Americas[58], while others do not[122]. However, in general, evidence from such studies weakly constrain the problem because Holocene carbon cycle modelling is designed to investigate changes associated with long-acting slow processes (carbon uptake by peat or coral reefs) and feedback mechanisms (oceanic outgassing, oceanic uptake and CO_2 fertilization of vegetation), and probably poorly represent the short period of the CO_2 dip (for example, ref. 57). For example, a study calculating a net zero impact of the cessation of farming in the Americas[122] included a large soil carbon flux to the atmosphere, which contradicts field evidence[120,123], and had the effect of offsetting the uptake from growing trees[122]. Carbon cycle models with robust representations of land-use change and subsequent vegetation regeneration following the Americas population catastrophe will be required to improve estimates of carbon uptake compared with carbon accounting studies.

The approximate magnitude and timing of carbon sequestration make the population decline in the Americas the most likely cause of the observed decline in atmospheric CO_2. Atmospheric[74,124,125] and tropical marine $\delta^{13}C$ analyses[126] also support uptake of CO_2 by vegetation rather than oceanic uptake. The 1600 Huaynaputina eruption in Peru[78,79] probably exacerbated the CO_2 minima, and a lagged oceanic outgassing in response to the land carbon uptake probably contributed to the fast rebound of atmospheric CO_2 after 1610[127]. In addition, multi-proxy reconstructions of temperature indicate that, after accounting for both solar and volcanic radiative forcing, additional terrestrial carbon uptake is required to explain temperature declines over the 1550–1650 period[107]. This is consistent with uptake by vegetation following the population crash in the Americas[107].

Definitions of the Industrial Revolution give an onset date anywhere between 1760 and 1880, beginning as an event local to northwest Europe[88]. Given the initial slow spread of coal use, ice core records show little impact on global atmospheric CO_2 concentration until the nineteenth century, and then they show a relatively smooth increase rather than an abrupt change, precluding this as a GSSP marker (Fig. 2). Similarly, other associated changes, including methane and nitrate[15], products of fossil fuel burning (including spherical carbonaceous particles[93] and magnetic fly ash[94]) plus resultant changes in lake sediments[95,96] alter slowly as the use of fossil fuels increased over many decades. Lead, which was once routinely added to vehicle fuels, has been proposed as a possible marker, because leaded fuel was almost globally used and is now banned[97]. However, peak lead isotope ratio values from this source in sediments and other deposits vary from 1940 to after 1980, limiting the utility of this marker. The Industrial Revolution thus provides a number of markers spreading from northwest Europe to North America and expanding worldwide since about 1800, although none provides a clear global GSSP primary marker.

The Great Acceleration

Since the 1950s the influence of human activity on the Earth system has increased markedly. This 'Great Acceleration' is marked by a major expansion in human population, large changes in natural processes[3,12,98], and the development of novel materials from minerals to plastics to persistent organic pollutants and inorganic compounds[41,47,97]. Among these many changes the global fallout from nuclear bomb tests has been proposed as a global event horizon marker[41,47]. The first detonation was in 1945, with a peak in atmospheric testing from the late 1950s to early 1960s, followed by a rapid decline following the Partial Test Ban Treaty in 1963 and later agreements, such that only low test levels continue to the present day (Fig. 2). A resulting distinct peak in radioactivity is recorded in high-resolution ice cores, lake and salt marsh sediments, corals, speleothems and tree-rings from the early 1950s onwards, declining in the late 1960s[15,99]. The clearest signal is from atmospheric ^{14}C, seen in direct air measurements and captured by tree-rings and glacier ice, which reaches a maximum in the mid- to high-latitude Northern Hemisphere at 1963–64 and a year later in the tropics[100]. Although ^{14}C has a relatively short half-life (5,730 years), elevated levels will persist long enough to be useable for several generations of geologists in the future.

While recognizing that many apparently novel industrially produced chemicals are occasionally produced in small quantities naturally[101], chemical signatures from long-lived well-mixed gases in glacier ice or sediments may also meet GSSP criteria. Potential long-lived gases are the halogenated gases, such as SF_6, C_2F_6, CF_4 (with half-lives of 3,000 yr, 10,000 yr and 50,000 yr, respectively). Most were first manufactured industrially in the 1950s, and many are measurable in firn air[102], and with large enough samples could be measured in ice cores[15]. But although they are measurable, distinct peaks are very recent and sometimes absent because major declines in industrial production are occurring after the negotiation and ratification of the 1989 Montreal and 2005 Kyoto protocols.

Of the various possible mid- to late-twentieth-century markers of the Great Acceleration, the global ^{14}C peak provides an unambiguously global change in a number of stratigraphic deposits. We suggest that an unequivocally annual record is the optimal choice to reflect the ^{14}C peak, thereby giving a dating accuracy of one year. We propose that the GSSP marker should be the ^{14}C peak, at 1964, within dated annual rings of a pine tree (*Pinus sylvestris*) from King Castle, Niepołomice, 25 km east of Kraków, Poland[103] (Fig. 2). Secondary correlated markers would include plutonium isotope ratios ($^{240}Pu/^{239}Pu$) in sediments indicating bomb testing[104], (fast-decaying) 137-Caesium[97], alongside the presence of peaks in very long-lived iodine isotopes (^{129}I, with half-life 15.7 million years) found in marine sediments[105] and soils[106].

While radionuclide fallout did not have major biological or other widespread physical repercussions, other auxiliary stratotypes may include the numerous other human-driven changes resulting in mid- to late-twentieth-century changes in geological deposits, including fossil pollen of novel genetically modified crops; declines in $\delta^{15}N$ in Northern Hemisphere

lakes[96] and ice cores[15]; the emergence of SF_6 and CF_4 from background levels[15]; lead isotopes in ice cores[15]; microplastics in marine sediments[97]; diatom assemblages in lakes in response to eutrophication[41]; and benthic foraminifera changes in marine sediments[41].

Dating the Anthropocene

We conclude that most proposed Anthropocene start dates, including the earliest detectable human impacts[42], earliest widespread impacts[45], and historic events such as the Industrial Revolution[1–3,39,40], can probably be rejected because they are not derived from a globally synchronous marker. Our review highlights that only those environmental changes associated with well-mixed atmospheric gases provide clearly global synchronous geological markers on an annual or decadal scale, as is required to define a GSSP for the Anthropocene. The earliest potential GSSP primary marker we identify is the inflection of atmospheric methane at 5,020 yr BP (Fig. 2; Table 1), but correlated auxiliary stratotypes are lacking. Thus, the CH_4 inflection is unlikely to be a strong candidate for the beginning of the Anthropocene. We find that only two other events—the Orbis spike dip in CO_2 with a minimum at 1610, and the bomb spike 1964 peak in ^{14}C—appear to fulfil the criteria for a GSSP to define the inception of the Anthropocene (Fig. 2; Table 1). While both GSSP dates have a number of correlated auxiliary stratotypes there are advantages and disadvantages associated with each.

The main advantage to the 1610 Orbis spike is the geological and historical importance of the event. In common with other epoch boundaries[10] this boundary would document changes in climate[87,107], chemistry[75] and palaeontological[65,85] signals. Critically, the transoceanic movement of species is an unambiguously permanent change to the Earth system[40], and such a boundary would mark Earth's last globally synchronous cool period[87] before the long-term global warmth of the Anthropocene Epoch. Historically, the Industrial Revolution has often been considered as the most important event in relation to the inception of the Anthropocene[1,2,39,40], but we have not identified a clear global Industrial Revolution GSSP. However, in the view of many historians, industrialization and extensive fossil fuel use were only made possible by the annexing of the Americas[88]. Before the Industrial Revolution both northwest Europe and southern China were similar in terms of life expectancy and material consumption patterns, including modest coal use, and both regions faced productive boundaries based on the available land area[88]. Thus, the agricultural commodities from the vast new lands of the Americas allowed Europe to transcend its ecological limits and sustain economic growth. In turn, this freed labour, allowing Europe to industrialize. That is, the Americas made industrialization possible owing to the unprecedented inflow of new cheap resources (and profitable new markets for manufactured goods). This 'Great Divergence' of Europe from the rest of the world required access to and exploitation of new lands plus a rich source of easily exploitable energy: coal[88]. Thus, dating the Anthropocene to start about 150 years before the beginning of the Industrial Revolution is consistent with a contemporary understanding of the likely material causes of the Industrial Revolution. The main disadvantage to the Orbis hypothesis is that a number of deposits may not show large changes around 1600, particularly in terms of biological material from the transport of species to new continents or oceans, because there are time-lags before species newly appear in geological deposits.

The key advantage of selecting 1964 as the base of a new Anthropocene Epoch is the sheer variety of human impacts recorded during the Great Acceleration: almost all stratigraphic records today, and over recent decades, have some marker of human activity. The latter part of the twentieth century is unambiguously a time of major anthropogenic global environmental impacts[108]. One disadvantage is that although nuclear explosions have the capacity to fundamentally transform many aspects of Earth's functioning, so far they have not done so, making the radionuclide spike a good GSSP marker but not an Earth-changing event. A further possible limitation in selecting such a recent date is that some deposits, notably some marine sediments, do not accumulate and stabilize over time spans as short as the past 50 years, making clear datable changes and correlation among some stratotypes sometimes difficult to discern[40].

Choosing between the 1610 Orbis and 1964 bomb spikes is challenging. As an alternative, a GSSA date, based on stratigraphic evidence, could be agreed upon by committee as the inception of the Anthropocene. However, any chosen date would be potentially open to challenge as arbitrary. For example, the Industrial Revolution is certainly a pivotal moment in human history, yet it is unclear how one could choose, based on the available geological evidence, an early Industrial Revolution GSSA date, say 1800, over a later date, perhaps 1850 or 1900. Similarly, the Great Acceleration is diachronous[108], and GSSA suggested dates could be 1945, 1950 or 1954 (ref. 109). Given such difficulties, given that GSSP markers are preferred[10], and given that candidate GSSP markers exist, a GSSA date seems unnecessary. Of the GSSP possibilities we tend to prefer 1610, because the transoceanic movement of species is a clear and permanent geological change to the Earth system. This date also fits more closely with Crutzen and Stoermer's original proposal[1] of an important historical juncture—the Industrial Revolution—as the beginning of the Anthropocene, which has been enduringly popular and useful, suggesting 1610 may be similarly so.

We hope that identifying a limited number of possible events and GSSP markers may assist in focusing research efforts to select a robust GSSP alongside a series of auxiliary stratotypes. Such research might include compiling data sets of the first appearance of non-native species in lake and marine sediments to better document the transoceanic spread of species and improve the evidence on which the 1610 proposal is based. The reliable detection of ^{129}I in high-resolution glacier ice and expanding the number of locations at which novel minerals, compounds and other recent human signals are investigated[41,47] would advance the 1964 GSSP proposal.

Ratification of an Anthropocene Epoch would require a further decision to be made, that is, whether to retain the Holocene Epoch (Fig. 1). All Anthropocene GSSP choices would leave a complete Holocene Epoch at least three orders of magnitude shorter than any other epoch[10] and similar to previous Pleistocene interglacials[55], which are not epoch-level events. Furthermore, the existence of a Holocene Epoch is due, in part, to the view—originating from nineteenth-century geologists—that the presence or influence of humans distinguished the Holocene from the Pleistocene[9,26,27,35,38]. An Anthropocene Epoch, combined with today's evidence that *Homo sapiens* is a Pleistocene species, removes key justifications for retaining the Holocene as an epoch-level designation. We therefore suggest that if the Anthropocene is accepted as an epoch it should directly follow the Pleistocene (Fig. 1c), as suggested independently elsewhere[110]. If the Holocene ceases to be an epoch but refers instead to the final stage of the Pleistocene Epoch, we suggest that the term Holocenian Stage is used, to maintain consistency with current terminology. While an alternative informal geological term, the Flandrian stage, denotes the current interglacial as part of the Pleistocene, its use has strongly declined over recent decades[10], and would not be as recognizable as the Holocenian Stage. Re-classifying any pre-Anthropocene Epoch interglacial time unit as the Holocenian Stage will create the usual tension[10] between resistance to altering past GTS agreements and the maintenance of GTS internal consistency.

The wider importance

The choice of either 1610 or 1964 as the beginning of the Anthropocene would probably affect the perception of human actions on the environment. The Orbis spike implies that colonialism, global trade and coal brought about the Anthropocene. Broadly, this highlights social concerns, particularly the unequal power relationships between different groups of people, economic growth, the impacts of globalized trade, and our current reliance on fossil fuels. The onward effects of the arrival of Europeans in the Americas also highlights a long-term and large-scale example of human actions unleashing processes that are difficult to predict or manage. Choosing the bomb spike tells a story of an elite-driven technological development that threatens planet-wide destruction. The

long-term advancement of technology deployed to kill people, from spears to nuclear weapons, highlights the more general problem of 'progress traps'[111]. Conversely, the 1963 Partial Test Ban Treaty and later agreements highlight the ability of people to collectively successfully manage a major global threat to humans and the environment. The event or date chosen as the inception of the Anthropocene will affect the stories people construct about the ongoing development of human societies.

Past scientific discoveries have tended to shift perceptions away from a view of humanity as occupying the centre of the Universe. In 1543 Copernicus's observation of the Earth revolving around the Sun demonstrated that this is not the case. The implications of Darwin's 1859 discoveries then established that *Homo sapiens* is simply part of the tree of life with no special origin. Adopting the Anthropocene may reverse this trend by asserting that humans are not passive observers of Earth's functioning. To a large extent the future of the only place where life is known to exist is being determined by the actions of humans. Yet, the power that humans wield is unlike any other force of nature, because it is reflexive and therefore can be used, withdrawn or modified. More widespread recognition that human actions are driving far-reaching changes to the life-supporting infrastructure of Earth may well have increasing philosophical, social, economic and political implications over the coming decades.

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