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Key Points:

- Humans refashioning relationship between production and consumption in the biosphere
- Biosphere characterized by pattern of global energy flow pervasively influenced by humans
- Changes consistent with the biosphere entering a new stage of its evolution

Supporting Information:

- Supporting Information S1

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The Anthropocene: a conspicuous stratigraphical signal of anthropogenic changes in production and consumption across the biosphere

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Abstract Biospheric relationships between production and consumption of biomass have been resilient to changes in the Earth system over billions of years. This relationship has increased in its complexity, from localized ecosystems predicated on anaerobic microbial production and consumption to a global biosphere founded on primary production from oxygenic photoautotrophs, through the evolution of Eukarya, metazoans, and the complexly networked ecosystems of microbes, animals, fungi, and plants that characterize the Phanerozoic Eon (the last ~541 million years of Earth history). At present, one species, *Homo sapiens*, is refashioning this relationship between consumption and production in the biosphere with unknown consequences. This has left a distinctive stratigraphy of the production and consumption of biomass, of natural resources, and of produced goods. This can be traced through stone tool technologies and geochemical signals, later unfolding into a diachronous signal of technofossils and human bioturbation across the planet, leading to stratigraphically almost isochronous signals developing by the mid-20th century. These latter signals may provide an invaluable resource for informing and constraining a formal Anthropocene chronostratigraphy, but are perhaps yet more important as tracers of a biosphere state that is characterized by a geologically unprecedented pattern of global energy flow that is now pervasively influenced and mediated by humans, and which is necessary for maintaining the complexity of modern human societies.

1. Introduction

Patterns of biological production and consumption of biomass, which ultimately underpin ecosystem services, have evolved over billions of years on Earth, since the origins of the biosphere deep in Precambrian time. Here we define production as using chemical or light energy to convert inorganic material to biomass. We define consumption as extracting energy from biomass (living or dead), and for the latter we

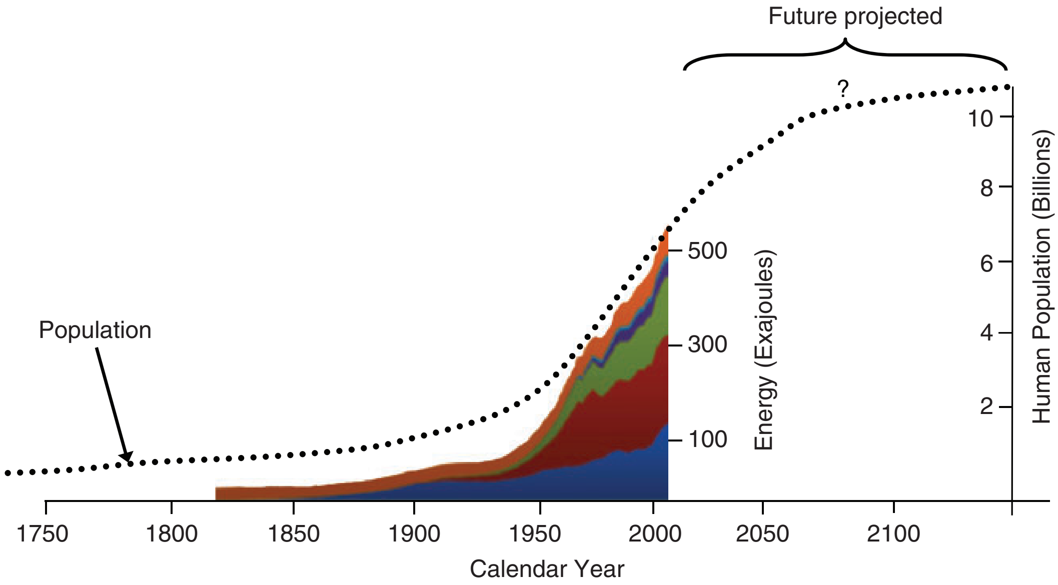

Figure 1. Produced energy and the pattern of human population growth from 1750. Utilization of these energy sources, together with the energy used by humans from net primary production, is now approaching the entire energy available to the global ecosystem before human intervention [*Barnosky*, 2015]. Key to colours: dark blue = coal; dark brown = oil; green = natural gas; purple = nuclear; light blue = hydro; orange brown = biomass (e.g. plants, trees). Data source from http://www.theoildrum.com/node/8936

are grouping animals and decomposers as consumers. Over the circa 4 billion years in which the biosphere has evolved, the mechanisms by which energy is stored and consumed have become more complex, culminating in the intricately networked marine and terrestrial ecosystems that have characterized Earth for the past half billion years. Scale and process in the Earth's biological-consumption system can be measured in a number of ways: a common one is Net Primary Production (NPP) — a measure of the net flux of carbon from the atmosphere into plants for a given time.

In geologically very recent times, humans have re-organized the patterns of biological production and consumption on Earth and their use in producing goods and services that also are consumed, primarily, by humans. Currently, humans appropriate between 25 and 38% of NPP [dependent on different estimates, see: *Haberl et al*., 2007; *Running*, 2012; *Krausmann et al*., 2013], they liberate considerable additional energy from fossil NPP [hydrocarbons such as coal, oil and gas; *Duke*, 2003], and, increasingly, produce energy from sources such as hydropower, solar radiation, wind, waves, geothermal sources, and nuclear reactors (Figure 1). This extra energy makes possible anthropogenically produced increases in what were previously primary limiting nutrients such as nitrogen, phosphorus, iron, and potassium. In tandem, the biology of the plants and animals that humans consume has also been manipulated, essentially to increase biological production [see *Williams et al*., 2015 for a review]. Human modification and appropriation of NPP, and the production of energy over and above NPP, has been developing over thousands of years, but accelerated markedly from the mid-20th century onward (Figure 1).

In this paper, we summarize the human impact on production and consumption within the biosphere, and ask whether the resulting patterns represent a wholesale change to the functioning of the biosphere comparable in its magnitude to other significant events in geological history. We also examine how human patterns of production and consumption leave a distinctive stratigraphic record, and evaluate whether this might be a means to identify or characterize an Anthropocene Series, the material (stratal) product of a putative Anthropocene Epoch [*Waters et al*., 2014, 2016; *Zalasiewicz et al*., 2014a, 2015].

2. Production and Consumption in the Biosphere Prior to Humans

A brief overview of the geological history of the relationships between the primary production of biomass (by chemical or photosynthetic mechanisms), and how the energy contained in that biomass is consumed by other organisms, is a necessary start point for assessing human impact, but also for understanding how

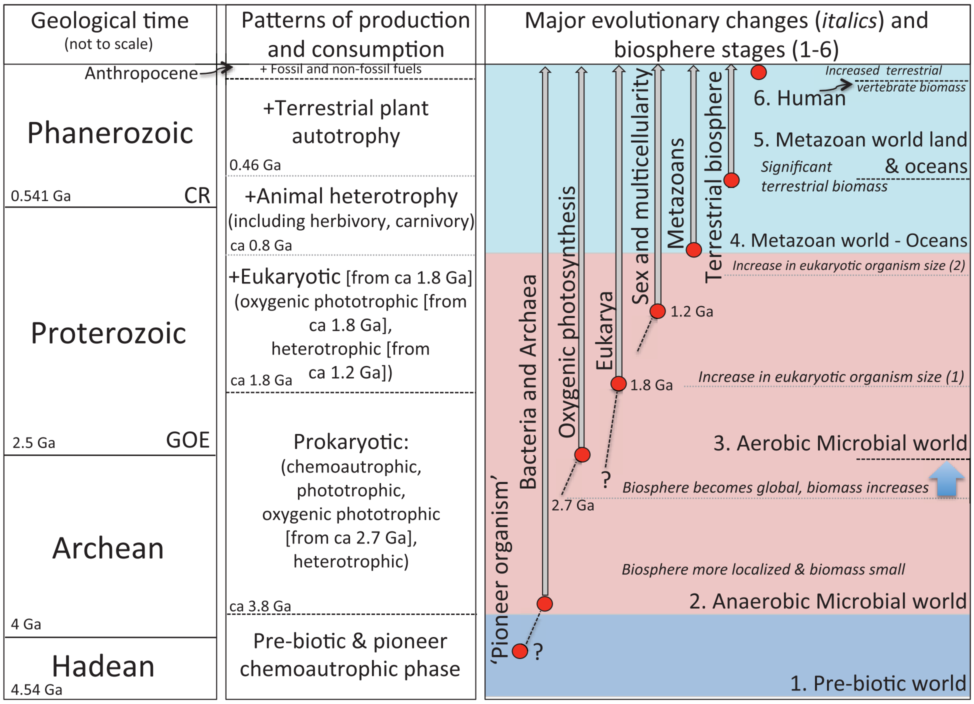

Figure 2. The four geological eons of Earth (left hand column) and the patterns of production and consumption that can be discerned from the fossil record (middle column). The right-hand column shows major events in the evolution of the biosphere that are linked to changes in the nature and location of primary production (e.g., origins of oxygenic photosynthesis, the development of terrestrial vegetation) and consumption (e.g., metazoan herbivory and carnivory). Text in italics indicates major steps in the development of different "reservoirs" of biomass in the biosphere. In the Archean, primary production was initially localized to volcanic/hydrothermal centers and was probably small, before becoming global and much more substantive with the evolution of oxygenic photosynthesis. Oxygenation may have provided one environmental trigger for increased eukaryotic organism size, first with cells in the Paleoproterozoic Era, and then with the Metazoa (animals) in the terminal Proterozoic Eon and early Cambrian Period [*Payne et al*., 2008]. Metazoans, evolving in the Late Proterozoic, radiated during the early Phanerozoic [*Butterfield*, 2011] to become the dominant component of marine standing biomass. The development of the terrestrial biosphere, from 460 million years ago, resulted in plants dominating the standing biomass, with significant feedbacks on climate. Megafauna standing biomass (including humans) rocketed from the beginning of the Industrial Revolution as humans used fossil fuels to augment the energy and nutrients available to the global ecosystem [*Barnosky*, 2008]. Biosphere stages 1 to 6 discerned here are *some* of the recognizable fundamental steps in the evolution of the global ecosystem, with humans (stage 6) identified as the most recent stage [*Williams et al*., 2015]. Abbreviations: GOE = Great Oxygenation Event (the development of an oxygenated atmosphere); CR = Cambrian radiation (or Cambrian "explosion").

biosphere complexity has developed (Figure 2). Reconstructing that history is predicated on a reading of the fossil record of the biosphere (Figure 3), and of molecular (genetic) evolution over long timescales. Despite being incomplete, this record identifies certain major events in the evolution of primary production, and of the trophic structure that developed to utilize the energy of production (summarized as stages 1–6 in Figure 2). It should be emphasized that our discussion is based on an emerging story of biosphere evolution over time, rather than representing a fixed record of sequential or directly connected events. An elegant, readable and detailed assessment of biological evolution on Earth is presented in *Nisbet and Fowler* [2014].

The biosphere probably began with a prebiotic phase of evolution [e.g., *Wächterhäuser*, 2006; Figure 2] that led to the development of cells as the primary mechanism for utilizing and storing energy, building biological materials (biomass), and processing those materials for the further release of energy. It also involved the development of RNA and ultimately DNA to convey information across generations [*Nisbet and Fowler*, 2014]. Initially the biosphere was structurally simple, with primary producers using chemoautotrophic pathways for production (organisms deriving energy from chemical reactions such as the oxidation of reduced compounds, see below).

Direct evidence of Earth's earliest ecosystems (Figure 2, anaerobic microbial world) is scant. Geological data show the existence of sulfur-reducing bacteria as early as 3.8 billion years ago [*Grassineau et al*., 2006] and carbon isotope data also suggest the action of organisms at a similar time [e.g. *Rosling*, 1999], and

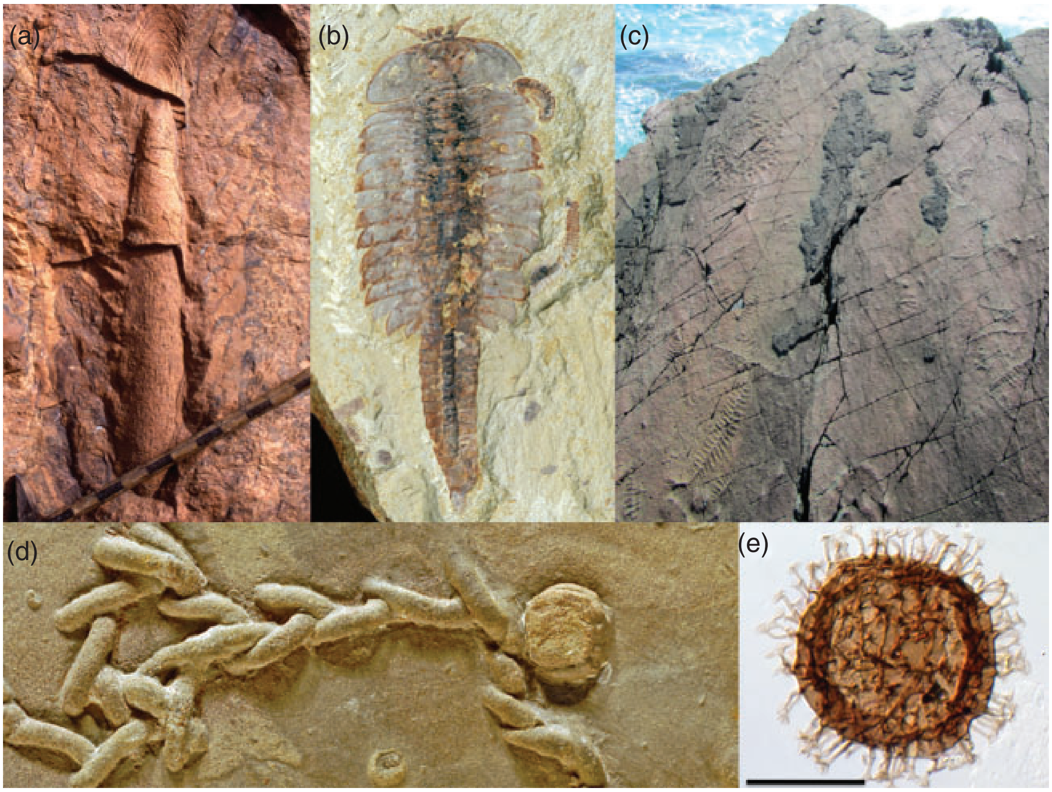

Figure 3. Examples of fossils that provide evidence for the evolution of production and consumption over geological time: (a) Stromatolites, an early example of ecosystem engineering constructed by colonies of prokaryotic cells, from the late Mesoproterozoic Era of Mauritania (image courtesy of Ian Fairchild, Birmingham University, scale bar is in cms); (b) fossil arthropod from the circa 525 million-year-old deposits of the Chengjiang Lagerstätte, Yunnan, China, indicating the emergence of bilaterian animals with skeletons and structures (guts, feeding appendages), some specifically adapted for predation or scavenging (image courtesy of Derek Siveter, Oxford University and Hou Xianguang, Yunnan University, fossil specimen is 6.1 cm long); (c) impressions of late Proterozoic (circa 565 million years old) Ediacaran biota on the ancient marine surface at Mistaken Point, Canada, representing Earth's first, widespread complex multicellular ecosystems (image courtesy of Latha Menon, Oxford University, foreground horizontal field of view is approximately 1 m); (d) early Cambrian trace fossils representing the action of bilaterian animals with directional movement through sediment (image courtesy of Jean Vannier, Lyon University, horizontal field of view about 6.35 cm), possibly using scavenging or predatory behaviour; (e) Cambrian acritarchs—a group with a record that extends deep into the Proterozoic Eon, and probably the resting cysts of unicellular eukaryotic phytoplankton that were important primary producers (image courtesy of Tom Harvey, Leicester University, scale bar is 20 µm).

perhaps even earlier, 4.1 billion years ago [*Bell et al*., 2015]. Fossil data indicate the presence of chemoautotrophic sulfur-metabolizing bacteria in the Paleoarchean geological record of Australia from 3.4 billion years ago [*Wacey et al*., 2011], with stromatolites (macroscopic structures formed by colonies of bacterial cells, see Figure 3a) of the same antiquity [e.g., *Allwood et al*., 2009]. Earth's earliest recognized organisms were prokaryotic cells, those organized like living bacteria and archaea, lacking a membrane-bound nucleus or organelles. Early means of energy production by these cells relied on chemical compounds associated with volcanic activity and were largely independent of the influx of solar radiation. This contrasts with the present situation, where the production of reduced organic molecules (CH_2O − carbohydrates) by oxygenic photosynthesis is the principal biological mechanism of primary (autotrophic) production of biomass.

Early habitats for life on Earth were probably varied. *Nisbet and Fowler* [2014] list zones where disequilibrium gradients could be maintained. Chemical disequilibrium exists where one chemical compound may change to another, in this process releasing energy that can be used by cells, as in the oxidation of ferrous iron to ferric iron (oxidation in this sense means the loss of an electron as Fe^{2+} transforms to Fe^{3+}, without necessarily including the agency of free oxygen). Disequilibrium is hence an essential prerequisite, providing an energy supply to living organisms (for where there is equilibrium, there is no energy available for use). Early environments for chemical disequilibrium on Earth were localized, and included hot hydrothermal settings, moderately warm settings, aqueous settings with metal and geochemical contrasts from hydrothermal input, and tidal waters where currents construct a nutrient flux. Early on, chemoautotrophic life used naturally occurring redox (oxidation/reduction) contrasts—probably resulting from hydrothermal exchanges between seawater (of high ionic strength) and hot igneous rocks. Such rocks, produced on the surface of the Earth by volcanic activity, are a source of many materials for chemical reactions that rely on disequilibrium (e.g., they are a primary source of reduced iron). Evolution may have proceeded rapidly from chemoautotrophic primary producers of biomass (Figure 2) to those cells that evolved primary (heterotrophic) consumption of that biomass: the accumulation of dead primary producer cells provided a source of reduced organic matter that could be utilized by cells evolving an oxidative process for energy release [*Nisbet and Fowler*, 2014]—though, again, at these early times typically using oxidants other than free oxygen (Figure 2). In this way the basic pattern of biological production and consumption that we are familiar with in the modern biosphere evolved very early. This early, pre-photosynthetic biosphere probably extended across the globe, but was limited to areas of volcanism and hydrothermal activity—the sources of chemical disequilibrium noted above. Major centers of hydrothermal activity and associated biological developments may well have been predicated on, as today, mid-ocean ridge crests located above centers of upwelling of magma. Vestiges of this early biosphere may be preserved in ancient submarine "pillow" lavas from 3.5 billion years ago [*Furnes et al*., 2004]. This biosphere was also probably supplied with energy sources from transient chemical species in the air (formed by the ionizing effects of UV radiation, in the absence, then, of an ozone layer) that could also be used to drive redox reactions for energy production. Importantly, in this early biosphere stage, overall productivity may have been small when compared to later photosynthesis-driven primary production [*Nisbet and Fowler*, 2014], marking a significant difference from later biosphere stages (Figure 2).

The evolution of photosynthesis provided the mechanism by which the biosphere became truly global (Figure 2, aerobic microbial world), independent of the chemical energy associated with volcanic centers [*Eigenbrode and Freeman*, 2006; *Nisbet and Fowler*, 2014]. Photosynthesis is evident in the geological record from patterns of carbon- and sulfur isotope fractionation from 2.7 billion years ago [*Grassineau et al*., 2002]. These patterns signal the activity of the Rubisco I enzyme that catalyzes carbon fixation in plants, though some mechanisms of anoxygenic photosynthesis may have existed much earlier, and were likely involved in the production of the distinctive Banded Iron Formations, laminated iron oxide/silica deposits that first appear about 3.5 billion years ago [*Kappler et al*., 2005] and provide the largest resource of iron ores used by humans. The evolution of oxygenic photosynthesis allowed the synthesis of carbohydrate using the energy of light, CO_2 as a source of carbon, and water as an electron donor (Figure 2), and thus freed organisms from the proximity of hydrothermal energy. The expansion of oxygenated ecosystems across the globe, which began in shallow marine environments [*Eigenbrode and Freeman*, 2006], effectively supplanted the dominance of earlier anaerobic systems. Photosynthesis remains the basis of most primary production of biomass on the Earth today.

Oxygenic photosynthesis using water and CO_2, and liberating free oxygen, made aerobic respiration possible. Free oxygen build-up in the atmosphere may have taken hundreds of millions of years from the first inception of photosynthesis, but is evident from geochemical signals by the Archean-Proterozoic boundary, 2.5 billion years ago (Figure 2), and, by oxidizing methane in the atmosphere and so reducing the levels of this powerful greenhouse gas, atmospheric oxygen may have caused a fundamental shift in climate, leading to the early Proterozoic glaciation [for a review see *Pufahl and Hiatt*, 2012]. The availability of free oxygen is also linked to the success of the Eukarya, which use specialized organelles, termed mitochondria, for aerobic respiration, and to increases in organism size [*Payne et al*., 2008].

The timing and mechanisms of the evolution of Eukarya, which are characterized by their membrane-bound nucleus and organelles, likely involved a symbiotic relationship between prokaryotic cells, as originally envisaged by *Margulis* [1976]. Eukaryotic cells allow for the compartmentalization of cellular functions such as photosynthesis in a chloroplast, or energy production within a mitochondrion. This is important, because within a single cell that byproduct of photosynthesis—oxygen—can immediately be used by mitochondria as an energy source. Some authors have suggested a deep Archean origin for Eukarya [see summary in *Nisbet and Fowler*, 2014]. Fossil evidence suggests the presence of eukaryotic cells in rocks from 1.8 billion years ago [*Knoll et al*., 2006; Figure 2] and of eukaryotic multicellular structures by 1.2 billion years ago [e.g., *Butterfield*, 2000].

The evolution of Eukarya was fundamental to patterns of production through eukaryotic phytoplankton and land plants (see below), and of heterotrophic consumption via, for example, herbivores, predators, scavengers, parasites, and fungi (Figure 2, metazoan world oceans). Eukarya developed tissue differentiation in multicellular structures [see *Ratcliff et al*., 2012 for a review of how this might have evolved], which led to the evolution of animals and higher plants, with their mechanisms for physical interaction with sediment in the oceans and on land [see also *Erwin*, 2008 in this context]. Although microbial communities are typically a few millimeters to centimeters thick on the surface of the Earth [though microbial communities can penetrate to levels of 1 km depth or more within the Earth's crust; *Parkes et al*., 2000], animals and plants physically invade sediments and soils to extract nutrients, enhancing primary productivity (e.g., via plant growth), and consumption (e.g., via predation and scavenging), and thereby engineering environments in which additional organisms can flourish to form complex ecosystems [*Erwin*, 2008; *Butterfield*, 2011]. The invasion of sediments—first in marine environments during the latest Proterozoic and earliest Cambrian—is sometimes referred to as the Cambrian "agronomic" (or "substrate") revolution [*Seilacher and Pflüger*, 1994]. It supplanted microbial mat ecosystems that had dominated the seabed in the Proterozoic, and opened a whole new range of environments that metazoans could utilize. Evidence for burrowing into seabed substrates (particularly trace fossils of the *Treptichnus pedum* assemblage) is taken to represent part of a fundamental transition between the mainly microbial ecosystems of the Archean and Proterozoic, and the metazoan-dominated ecosystems of the Phanerozoic (see Section 5.1 below).

Ascertaining the mechanisms and timing of evolution of metazoans (animals) from single-celled eukaryotic precursors has vexed geologists and paleontologists for over a century, but the succession of events indicated by molecular analyses of animal evolution—only partially recorded in the fossil record—gives an indication of the origin of animals about 800 million years ago [Figure 2; for a summary see *Erwin et al*., 2011]. This involved the evolution of efficient systems for concentrating organic matter in large bodies [e.g., *de Goeij et al*., 2013], and elevated the standing marine biomass through the evolution of animals [*Butterfield*, 2011]: animals then formed the bulk of standing marine biomass throughout the Phanerozoic Eon (the past ~541 million years of Earth history). Earth's earliest animals included sponges, ctenophores (comb jellies), and cnidarians (medusoids, anemones etc.) that use filter feeding, water currents and blind guts (gastrovascular cavities) to ingest food. Earth's earliest ecosystems preserving possible metazoans are those of the Ediacaran biota, which may include putative animals, fungi, algae, protists and others—[*Xiao and Laflamme*, 2009] from circa 580 to 541 million years ago (Figure 3c). Ediacaran communities included organisms that may have used a range of strategies for feeding, including osmotrophy [*Ghisalberti et al*. 2014; *Xiao*, 2014; Figure 3c], and possible bilaterian animals—those with a clearly identifiable anterior and posterior end and directional locomotion, enabling burrowing into substrates [*Jensen*, 2003]. The development of bilaterian guts [see *Vannier and Chen*, 2002; *Vannier et al*., 2014], and of life strategies—and associated appendages, to trap prey, or conversely through the evolution of skeletons, to avoid being preyed upon, led to the development of complex multi-tiered trophic structures in marine and then terrestrial foodwebs, between primary producers of biomass (e.g., marine phytoplankton, land plants) and the consumers of biomass at different trophic levels (e.g., herbivores, predators, scavengers), including large apex predators. It is this level of organization that has characterized the past half billion years of biosphere evolution (the Phanerozoic Eon), in which no single species has dominated production or consumption (cf. Figure 4). This system has been subject to, but also resilient toward, mass extinction events [*Barnosky et al*., 2012].

Acritarchs (Figure 3e) are considered to be the cysts of probable planktonic eukaryotic algae that first occur in the fossil record of the Paleoproterozoic Era. A terrestrial microbial biosphere may have evolved as early as the Archean [see *Beraldi-Campesi*, 2013 for a review], with a widespread photosynthetic community developed on land by the Late Proterozoic [*Knauth and Kennedy*, 2009]. Spore assemblages indicate that plants began colonizing the land during the Ordovician Period, some 460 million years ago [*Wellman et al*., 2003] as the initial stage in the development of significant terrestrial primary production (Figure 2, metazoan world land and oceans). In contrast to marine ecosystems (see above), where animals are the largest component of standing biomass, on land, plants are the largest standing biomass.

The extension of this terrestrial biosphere of plants and animals from its beginnings in the Ordovician and Silurian periods, to the much more extensive forests of the mid and later Paleozoic is recorded in the fossil record. Megascopic evidence of the first plants with vascular tissues [*Edwards et al*., 1992], which evolved on land during the Silurian Period about 430 million years ago, was followed by a great explosion of

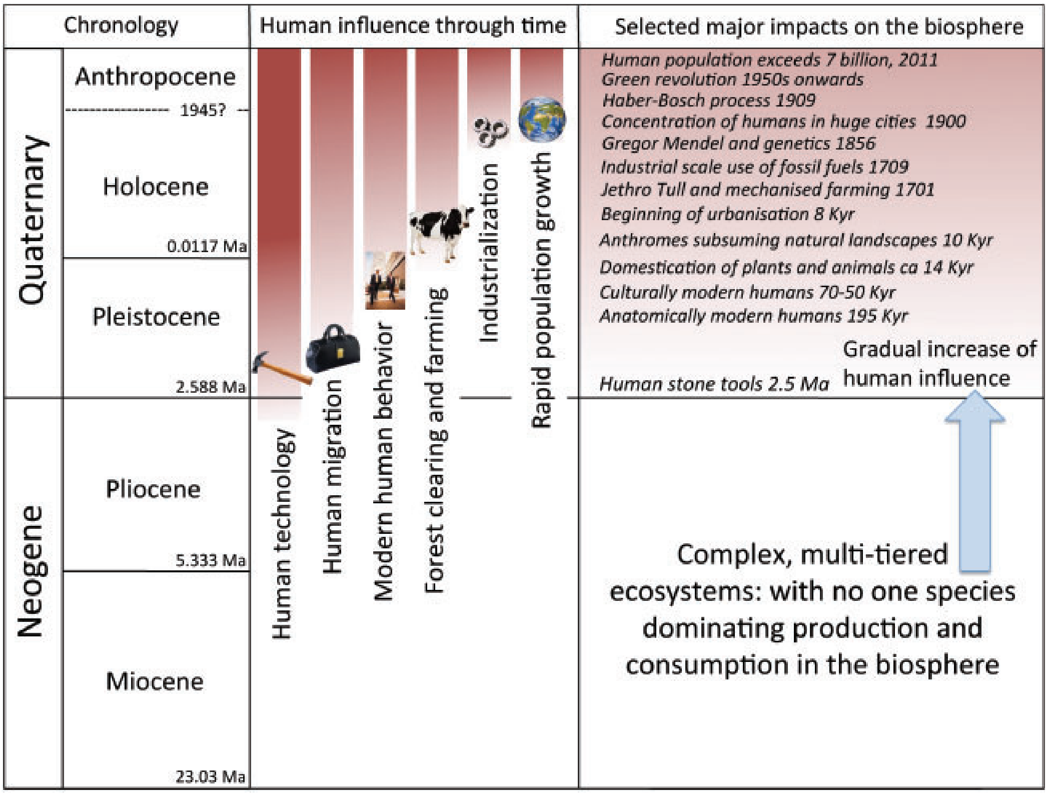

Figure 4. A chronology of the human influence on patterns of primary and secondary production, and consumption, and on energy use from fossil fuels, from the late Pliocene to present. The figure identifies key factors in the human appropriation of primary and secondary production, via technology (and technofossils), migration (see Figure 5), cultural evolution (from circa 70,000 years ago, culturally modern humans), forest clearance and farming, industrialization (and use of fossil fuels), and the consequent 20th–21st century surge in population growth. These changes are reflected in physical strata through the manifestation of "Boundary A," sensu *Edgeworth et al*. [2015], the diachronous bounding surface which marks the base of anthropogenic deposits, above which is a lithostratigraphic entity that contains novel materials and remains of domesticated animals and plants found as inclusions in anthropogenic ground—a direct signal of the increasing impact of humans. Right-hand column shows selected and illustrative (but not exhaustive) major impacts on production and consumption in the biosphere. References to industrial scale consumption of fossil fuels (fossil NPP) in 1709 refer to Abraham Darby's use of charcoal for iron smelting at his Shropshire Coalbrookdale factory, often viewed as the "birthplace" of modern industry. Jethro Tull's development of the horse-drawn seed drill and hoe contributed to what is called the British Agricultural Revolution, and forms part of a broader continuum of agricultural developments beginning in medieval and early modern Europe and elsewhere.

diversity during the Devonian Period (~419-359 million years ago). By the Mid Devonian the first forests had appeared [*Stein et al*., 2012]. During the Late Devonian large, deep-rooted vascular plants became common, and seed plants that could reproduce in drier habitats became widespread, increasing the depth and rate of physical and chemical weathering and probably affecting both fluvial landscapes [*Davies and Gibling*, 2010] and the global carbon cycle [*Berner*, 1998; *Driese and Mora*, 2001]. During the late Carboniferous and early Permian (~320–270 million years ago), extensive peat formed under tropical wetland forests forming much of the fossil NPP (coal) that is currently consumed by humans (Figure 1). High southern latitude glacial conditions that characterized the late Carboniferous and early Permian waned in the later early Permian, seasonality of precipitation increased in the tropics, restricting wetland vegetation to smaller areas and leading to the expansion of vegetation dominated by seed plant groups such as cycadophytes and conifers [*DiMichele et al*., 2009]. During much of the Triassic and Jurassic periods warm global climate persisted and vegetation was dominated by a combination of ferns, conifers, and a diversity of now-extinct orders of seed plants. Angiosperms (flowering seed plants) first appeared in the Early Cretaceous, diversified rapidly, and achieved high abundance across a wide spectrum of landscapes and climate types in the Late Cretaceous [*Wing and Boucher*, 1998; *Lupia et al*., 1999; *Feild et al*., 2011]. Though grasses evolved in the Late Cretaceous, grasslands appear not to have become widespread until the mid- to late-Cenozoic, when many of the lineages of greatest importance to agriculture began to diversify [*Strömberg*, 2011, see Section 5.1 below].

Producer/consumer interactions on land developed as terrestrial environments were colonized in the Paleozoic Era. The co-evolution of arthropod consumers and plants is well documented, with early examples from the late Silurian of myriapod, apterygote and hexapod herbivory on primitive vascular plants, as well as on the large, enigmatic, fungus-like organisms such as *Prototaxites* [*Labandeira*, 2006]. During the early Carboniferous an expansion of plants and herbivorous insects and mites occurred, with adaptations to specialized feeding on leaves, seeds, true roots, and wood [*Labandeira and Currano*, 2013]. Many other trends in co-evolution are recorded in the geological record, for example the apparent relationship between primate diversity and the availability of fleshy fruits in the Cenozoic [*Collinson and Hooker*, 1991].

During the Phanerozoic Eon, the metazoan, macro-plant and microbial components of the biosphere have been successful in recycling the materials necessary for life on Earth, recovering life's complexity in post-extinction intervals over the duration of several million years [e.g., *Chen and Benton*, 2012], and without any one species dominating production or consumption. This pattern is now being re-organized by the influence of humans on terrestrial NPP, by increasing the standing biomass of herbivores (through the domesticated animals that we eat), and by effectively supplanting top predators in marine and terrestrial settings. It has produced a markedly changed landscape [*Ellis and Ramankutty*, 2008; *Ellis et al*., 2013], effectively subsuming natural (at most lightly impacted by humans) ecosystems into anthromes (anthropogenic biomes). This process has been accelerated through the use of energy from fossil fuels (Figure 2, human world, stage 6), and is reminiscent in its impact, magnitude and global extent to past stages of biosphere evolution, where earlier widespread ecologies (e.g., anaerobic microorganisms in shallow marine settings of the Archean, or microbial mats at the seabed in the Proterozoic) were supplanted by new ecosystem types through biological innovations such as oxygenic photosynthesis and burrowing, or in the contemporary world by some of the innovations summarized in Figure 4.

3. How and When Did Humans Change Patterns of Production and Consumption?

The human impact on production and consumption in the biosphere is recognizably different from all previous patterns. Humans appropriate a major component of NPP that is augmented by their use of fossil fuels [*Vitousek et al*., 1986; *Barnosky et al*., 2012, 2015; *Bonhommeau et al*., 2013]: the combined energy use now approaches that available to the entire terrestrial biosphere prior to human intervention [*Barnosky*, 2015]. In addition, humans are poor at recycling compared to the unmodified biosphere [*Haff*, 2014], a clear example being the geologically unprecedented rapid increase of carbon in the atmosphere from the consumption of fossil fuels, and concomitant accumulations of plastics—made from hydrocarbons—at the surface [*Zalasiewicz et al*., 2016].

Organisms have been engineering their environment since prokaryotic cells first constructed stromatolite structures in the Archean Eon [*Erwin*, 2008; see also Figure 3a]. Processes such as the accumulation of shelly material, or bioturbation at the seabed, can produce new ecological niches that may foster biodiversity. Among many examples, *Erwin* [2008] cites mangroves, arising in the Late Cretaceous (at circa 120 million years ago), as nurseries for coral-reef fish. Although many species are ecosystem engineers, such as beavers [*Wright et al*., 2002] or large herbivores like elephants and wildebeest, conspicuously modifying the environment around them [*Estes et al*., 2011; Barnosky *et al*., 2015], or use tools for direct intervention in their environment, [e.g., corvids and chimpanzees, e.g. *Boesch and Boesch*, 1990; *Koops et al*., 2015], only humans use technology to modify Earth's environment at a global scale (Figure 4). The process leading toward human global technological impact on the environment is evident in the fossil record of the development of stone tools, possibly beginning as early as the late Pliocene, more than 3.4 million years ago [e.g., *McPherron et al*., 2010], and showing increasing complexity from the Paleolithic to the Neolithic cultures. Anatomically modern humans originating in Africa at circa 195,000 years B.P. [*McDougall and Fleagle*, 2005], and developing Upper Paleolithic stone blade technologies from circa 50,000 years ago [*Bar-Yosef*, 2002], extended the use and impact of their technology as they migrated across the planet (Figure 5). Though multiple stressors, including climate change, may have been involved, some of the megafaunal extinctions (of animals weighing greater than 44 kg) follow the appearance of anatomically modern humans in Australasia] about 46,000 years ago; *Roberts et al*. 2001], and in the Americas [15,000–14,000 years ago; *Koch and Barnosky*, 2006; *Barnosky et al*., 2014]. Dating of artifacts from the Middle Stone Age in Africa provides evidence for the evolution of modern behavioral traits in humans before 70,000 years ago, signaled by engraved abstract

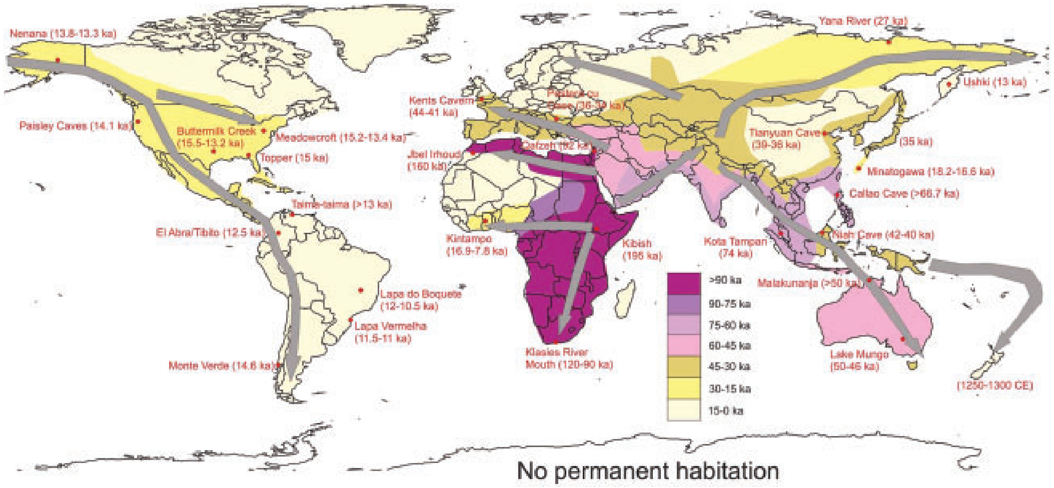

Figure 5. The pattern of global migration exhibited by *Homo sapiens* from the Paleolithic culture to present (compilation of data sources are indicated in Appendix S1, Supporting Information).

representations on pieces of ochre at the Blombos cave site in southern Africa [*Henshilwood et al*., 2002]. Behavioral traits such as large-scale social organization and forward planning facilitated a greater influence of humans on their surroundings and are seen as critical characteristics of the Anthropocene biosphere [*Ellis*, 2015; *Williams et al*., 2015]. Global human population may also have increased at this time [*Aiméa et al*., 2013].

The influence of humans on mammal populations during the late Pleistocene represents a global, though diachronous, signal of growing human impact. This potentially had an ecosystem engineering effect, as the climax forests of several areas throughout North America may be the result of the removal of megafauna (mammoths and mastodons) in the late Pleistocene, animals that were effective in forest clearance [*Gill et al*., 2009; *Barnosky et al*., 2015]. However, a key transition in the human remodeling of production and consumption was the origin of farming, moving primary productivity to annual crop plants and shifting primary consumption to domesticated animals. These innovations, which mark the end of the Epi-Paleolithic and the beginning of the Neolithic culture, include the domestication of cattle (pigs, cows, goats, sheep etc.) and development of agriculture from about 10,000 years ago [*Weisdorf*, 2005]. Once adopted, agriculture sustained a greater population (and standing biomass) of people, and provided the environment in which human specialist activities unrelated to food production could evolve [*Weisdorf*, 2005], facilitating the development of complex human societies, and the structures that support them. In this sense the Neolithic agricultural revolution might be compared to the impact of the Cambrian agronomic revolution. It was associated with greater complexity [if expressed in terms of human systems including the technosphere, *Haff*, 2014, and see below], with changed trophic relationships (with the human species supplanting apex consumers in marine and terrestrial settings), and with elevated standing biomass in animals (in the human case with terrestrial vertebrates, as opposed to invertebrates in marine settings of the Cambrian). Growth in human population, from perhaps circa 1–10 million at 10,000 years BP, 200–400 million at 1 AD, to circa 1 billion people by 1800 AD [see *United States Census Bureau*, 2015 figures version accessed in July 2015], together with the spatial expansion of agriculture and domesticated animals across the globe [*Crosby*, 2004], and from multiple early origins, for example in the Middle East, East Asia and Mesoamerica, and from multiple sources even within a single region [*Diamond*, 2002; *Fuller et al*., 2011], contributed to increasing appropriation of production through this time interval. Over the past two millennia a pattern of human- and climate-induced changes to biomass burning is also evident with, most notably, an interval of reduced burning from 1870 onward that likely reflects the influence of managed landscapes that are intensively grazed and cropped [*Marlon et al*., 2008].

The eventual transfer of labor from agriculture to non-agricultural activities is the central component of industrialization, and has led to even greater appropriation of primary production by humans, and to the use of fossil fuels to augment energy supplies to the global ecosystem, with the concomitant rise of humans and their domesticated animals as the principal component of standing terrestrial large-animal biomass [*Barnosky*, 2008; *Smil*, 2011]. From the 17th- to mid-20th century technological advances in farming, in their initial stages focused on England, the Low Countries and northern Italy, and then spreading globally, helped facilitate increasing appropriation of primary production. These included: improvements in drainage and restoration systems; the development of the Dutch plough in the early 17th century; the mechanization of farming in the early 18th century; developments in breeding and genetic manipulation, scientifically explained by Gregor Mendel in the mid-19th century; and the use of fertilizers, with the discovery that ammonia could be synthesized by a chemical reaction from nitrogen, first demonstrated by Fritz Haber in 1909, representing perhaps the most significant step (Figure 4). This paved the way for overcoming a major natural limiting force on agricultural production—the rate at which plants fix atmospheric nitrogen into soils [*Perkins*, 2011]—in the early 20th century by the German scientists Fritz Haber and Carl Bosch, who used Haber's earlier discovery to develop the Haber-Bosch process. Their process took atmospheric nitrogen to make nitrogen fertilizers [some 90 million tons of nitrogen-based fertilizer now being produced each year, *Holland et al*., 2005]. Through enhancing food production, this single innovation is estimated to sustain some 40% of global human population today [*Cornell*, 2010]. The process is energy-intensive, and is directly supported by the consumption of fossil fuels (fossil NPP). The widespread use of fossil energy (Figure 1) to make processing of land (e.g., ploughing) quicker and more efficient, to support a greater number of humans and their domesticated animals, to enable rapid national/international transfer of produce, and to enable more efficient harvesting of the sea and sea floor has further amplified the impact of humans on both production and consumption in the biosphere.

During the 20th century (between 1910 and 2005) the Human Appropriation of Net Primary Productivity doubled from 13 to 25% of the NPP of potential vegetation [*Krausmann et al*., 2013]. These changes involved a doubling of reactive nitrogen [*Galloway et al*., 2008] and phosphorus [*Filippelli*, 2002] in the environment, and the use of vast amounts of fossil energy focused on agricultural production. In 2014 humans extracted 225 million tons of fossil phosphates, and this is projected to rise to 258 million tons by 2018 [*USGS*, 2015]. Phosphates are a limited resource, but nevertheless annual human addition to the phosphorus cycle exceeds the amount of available phosphorus from natural recycling [*Rockström et al*., 2009]. Future projections, dependent on land-use, suggest between 27 and 44% of NPP might be appropriated by humans by 2050 [*Krausmann et al*., 2013]. While it is likely a geologically unique situation for a single species to co-opt or consume such a large percentage of NPP, perhaps more significant from a biosphere perspective is the technology and landscape modification that humans have used to achieve this. This leads to a complex relationship whereby the ultimate biophysical limit to the amount of NPP that humans might appropriate [see *Running*, 2012] is dependent on the interplay of many parameters in the landscape [*Erb et al*., 2012], a relationship that needs to evolve rapidly to provide stability between production and consumption in the Anthropocene biosphere.

Viewed from another perspective, the large-scale integration of humans and technology has led to a new terrestrial "sphere," the technosphere [*Haff*, 2014], a novel Earth system of global extent, which is characterized by a total mass approaching that of the biosphere, significant rate of energy dissipation (17 TW), and high average density of infrastructure links such as roads [circa 0.4 km of roadway per km^2 of land area, *CIA*, 2015] and of links between mobile communication devices [circa 50 such devices per km^2 of land area, *PR Newswire*, 2014] that help connect together most humans and most in-use technological artifacts. An emergent system, the technosphere comprises the world's humans, cultures, and technological components and systems, and maintains itself quasi-autonomously via feedback loops that deliver goods and services desired by humans (e.g., entertainment), or essential for their survival (e.g., food and water), in return for human participation in its continued function. There are no analogs for the technosphere in the geological history of life on Earth. Therefore, its myriad ramifications are truly unprecedented.

4. Human Impact Measured Against Geological Events

Throughout geological history the coupling between the production of biomass and the consumption of that biomass in the biosphere has typically maintained stability, with periods such as the Ordovician and Cretaceous showing patterns of fauna and flora that indicate persistent stable ecosystems over long time frames. Intervals where this stability may have been temporarily disrupted include the mass extinction events of the Neoproterozoic Era and Phanerozoic Eon [there being six of these following the definition of *Benton*, 2012, of which five were within the Phanerozoic Eon], with many small-scale extinctions operating at intervals of perhaps hundreds of thousands of year timescales or less. More fundamental changes to the functioning of the biosphere are associated with: its expansion to cover much of the globe (with increasing primary production) during the evolution of photosynthesis at circa 2.7 billion years ago [*Nisbet and Fowler*, 2014; see Figure 2] linked to the development of an oxygenated atmosphere during the Great Oxygenation Event beginning circa 2.5 billion years ago [*Pufahl and Hiatt*, 2012]; the construction of complex trophic structures between primary producers (e.g., marine phytoplankton), primary consumers (e.g., herbivorous zooplankton), and secondary consumers (e.g., tertiary and apex arthropod predators) during the Cambrian Period [*Butterfield*, 2011; *Perrier et al*., 2015], which led to animals typically forming the largest standing biomass in marine ecosystems; and the construction of complex terrestrial ecosystems with plants forming the largest standing biomass, with an increasing impact on the carbon-cycle and climate during the mid-Paleozoic [*Kansou et al*., 2013] and later. Measured against these changing geological-scale patterns, is the human impact on the biosphere significant?

Certain characteristics of current production and consumption in the biosphere appear entirely unique from a geological perspective, not least in being driven by a single species (*Homo sapiens*) within a time frame that is dramatically accelerated (decades versus millions of years) relative to past events. These changes have been characterized as defining a new biosphere state [*Behrensmeyer et al*., 1992; *Williams et al*., 2015]. They include the widespread transportation of animals and plants around the planet (the "neobiota"), the human-directed evolution of biology and ecosystems, the extraction of energy and material resources from deep in the Earth's crust, and the huge appropriation of production by humans, which will leave a fossil record in, for example, both the physical and chemical signatures of biomineralized materials [bones, shells, reefs, etc., see *Kidwell*, 2015].

A profound example of these changing patterns is the Green Revolution of the mid-20th century. This translation of technologies that originated from technological breakthroughs in developed countries, which were transported and adapted to the developing world, included the transfer of technology for fertilizers (principally nitrogen-, phosphate- and potassium-based), new crop varieties, insecticides, pesticides, herbicides and irrigation. The Green Revolution spread across the world from the 1950s onward, dovetailing with the Great Economic Acceleration in industrialized nations [*Steffen et al*., 2007, 2015]. It led to the doubling of appropriation of NPP by humans through the 20th century [*Krausmann et al*., 2013] and a concomitant rise in the consumption of fossil NPP to support that. This redirection of resources along different biological paths has led to humans and their domesticated animals comprising 175 million tons of carbon (estimates based on dry mass of 45% carbon) at the end of the 20th century, whilst wild terrestrial mammals represent just 5 million tons of carbon [*Smil*, 2011]; the total standing biomass of large terrestrial vertebrates in itself has been increased by about an order of magnitude over a "natural" baseline level by the tightly controlled and directed hyper-fertilization of terrestrial primary production [*Barnosky*, 2008].

Analyses suggest that human influence on the Earth's biota is promulgating a contemporary mass extinction event [*Barnosky et al*., 2011, 2012, 2014; *Kolbert*, 2014; *Pimm et al*., 2014; *Ceballos et al*., 2015] comparable to the five most significant events of the Phanerozoic Eon. This potential Anthropocene mass extinction event, if it continues to unfold, would thus immediately succeed (stratigraphically) a major perturbation of the nitrogen cycle (from the Haber-Bosch process) that is leaving a geochemical signal in sedimentary deposits worldwide, and it would also be associated with changes in carbon isotope ratios in marine carbonates as a result of the anthropogenic CO_2 emitted from the burning of hydrocarbons (a characteristically depleted ^{13}C signature). These signatures would resemble in magnitude, though not in environmental forcing, patterns of chemical change in the physico-chemical stratigraphic record, in part suggesting changes in the make-up of primary producer versus consumer organisms, and which are features of earlier extinction events such as in the latest Proterozoic [reduced acritarch phytoplankton diversity as a result of surface ocean eutrophication, *Nagy et al*., 2009], or at the Precambrian-Cambrian boundary [perhaps reflecting changes to surface-ocean primary production as a result of acritarch extinction, see *Zhu et al*., 2006 for a summary].

The human impact is not restricted to the land. The scale of appropriation of marine biological production by a single species (*Homo sapiens*) is almost certainly unique in Earth history, far exceeding the grazing of mainly coastal waters by, for example, seabirds (and, before them, flying reptiles), or pinnipeds. The rates of domestication of marine plants and animals are rising rapidly [*Duarte et al*., 2007]. Although fish farming dates back over 2000 years [e.g., *McCann*, 1979], with early examples in Australia, East Asia and Europe, it was quantitatively trivial, except locally, until 1970. Since that time aquaculture has become a significant component of fish consumption [*Naylor et al*., 2002], and this is sometimes referred to as the "blue revolution": in 2012 total world fisheries amounted to 158 million tons, of which 42% was aquaculture [*FAO*, 2014]. Having removed most top predators from the oceans, including by some estimates 90% of the largest predatory fish stocks [*Jackson*, 2008], humans are steadily fishing down the food chain [*Pauly et al*., 1998; *WBGU*, 2013]—in aggregate, 38% of marine fish have been lost, and the decline in certain baleen whales is up to 90% [*McCauley et al*., 2015]. At the same time, humans are continually harvesting, via a massive extension of bottom trawling powered by fossil fuels, the majority of the continental shelf, ranging now down onto parts of the continental slope [*Puig et al*., 2012]. Regions of the ocean undergoing fishery collapses are incapable of providing a full complement of ecosystem services, including those necessary to sustaining ever-growing human coastal populations [*Worm et al*., 2006].

Thus, it can be argued that the scale of human change to the biosphere with its transformation of terrestrial and marine ecologies, its use of fossil fuels to elevate the energy available to the global ecosystem, its impact on the standing biomass of terrestrial vertebrates, and its displacement of apex predators in both terrestrial and marine foodwebs, is of the magnitude of past major changes in the biosphere as shown in Figure 2.

5. A Physical Stratigraphical Signal of the Human Impact on the Biosphere

Here we review how past changes to production and consumption within the biosphere have left a stratigraphic signal that is sometimes useful in defining chronostratigraphic boundaries, but almost always useful in trying to quantify the sum of changes between different chronostratigraphic units—the time-rock units that geologists use for global correlation. The definition of chronostratigraphic units provides an essential common language between geologists: it is the scaffolding on which the history of Earth—including the evolution of the biosphere—can be assembled through time. We then examine the human impact on production and consumption in the biosphere from a stratigraphic perspective, and ask whether this might be useful for defining an Anthropocene chronostratigraphic unit, or for quantifying the sum of change between Holocene and Anthropocene epochs.

5.1. The Pre-Human Stratigraphic Signal

Physical stratigraphical indicators (fossil, sedimentological, and chemical) of past major changes to patterns of production and consumption form distinctive signals in the geological record. The development of primary production itself is signaled by changes to the ratio of the carbon and sulfur isotopes in rocks of the Paleoarchean Era [e.g., *Rosling*, 1999; *Grassineau et al*., 2006]. The origins of oxygenic photosynthesis are signaled by geochemical, sedimentological, and climatic changes that straddle the boundary between the Archean and Proterozoic eons 2.5 billion years ago [*Pufahl and Hiatt*, 2012]. Macrofossils (those visible to the naked eye) provide a spectacular record of changes to global ecosystems—and modes of consumption (e.g., herbivory, predation and scavenging) through the Precambrian-Cambrian transition (Figures 2 and 3). Also, micro- and macrofossils provide widespread evidence of the evolution of land-based terrestrial ecosystems from the early Paleozoic Era onward [*Wellman and Gray*, 2000], and thus of the development of terrestrial primary production and standing biomass.

Physical stratigraphical signatures of fundamental changes in patterns of biosphere production and consumption have provided useful data for defining chronostratigraphical boundaries and chronostratigraphic units, most notably the boundary between the Proterozoic and Phanerozoic eons (strictly "eonothems"; also the boundary between the Ediacaran and Cambrian systems, dated to ~541 million years ago). This stratigraphical boundary is based on the appearance of the distinctive *Treptichnus pedum* trace fossil suite in sedimentary rocks [see *Landing et al*., 2013], and as noted above, this identifies the actions of an increasingly diverse assemblage of bilaterally symmetrical animals with guts [e.g., see *Vannier et al*., 2010; and Figure 3d], marking fundamental and global changes to animal behavior and utilization of materials at and within the seabed [*Williams et al*., 2014 for a summary].

Other boundaries are based on a collapse of a large part of the global trophic structure—though in these cases caused by extrinsic factors such as environmental change or bolide impact—rather than by biological innovation itself, and noted most abruptly at the Cretaceous-Paleogene boundary [*Zachos et al*., 1989;

Schulte et al., 2010], but also at the other major boundaries based on mass species extinction events: the Ordovician-Silurian boundary, the Permian-Triassic boundary, and the Triassic-Jurassic boundary [see *Benton*, 2012 for an overview]. More modest, but still substantial, restructurings of this kind are commonly the basis for defining epoch- and age-level events, such as the boundaries between the Llandovery and Wenlock, and the Wenlock and Ludlow epochs of the Silurian Period [*Melchin et al*., 2012].

Yet other chronostratigraphic units have a significant biological component to their definitions, which signal global changes in biosphere evolution, ecosystem structure, and production and consumption of energy. Though not instrumental in defining a chronostratigraphic boundary *per se*, examples of this include the Ediacaran System (which immediately underlies the Cambrian System), which has, as one of its defining characteristics, evidence for a globally distributed macro-biota (the "Ediacaran biota," Figure 3c), representing the development of complex marine ecosystems. A further deep-time example is the Proterozoic Eon, which literally means "earlier life," and which is associated with the build-up of free oxygen via oxygenic photosynthesis, again marking a fundamental change in patterns of primary production on the Earth (Figure 2).

More recently, the stratigraphic signature of the rise of C_4 plants provides a pattern of biosphere change in terrestrial primary production that might form a useful comparison with the stratigraphic impact of human-induced changes to energy production (see below), particularly in the "slow" stratigraphic build-up of fossil and chemical data that signal the growing dominance of C_4 plants. In this case the geological data are too imprecise to provide stratigraphically useful definitions for chronostratigraphic boundaries (they cannot be used to recognize and correlate an isochronous surface globally, because they become important at different times in different continents and regions), but they are of critical importance in exploring changes in NPP during the Cenozoic Era.

C_4 photosynthesis arose independently in 3 families of monocots and 16 dicot families [*Sage*, 2004]. C_4 plants have a known fossil record from about 12 million years ago, but molecular evidence (gleaned from the rate of genetic mutations in the DNA of C_4 plants) places the origins of this mode of carbon fixation somewhat earlier than the fossil record, between 32 and 25 million years ago. The reduced abundance of atmospheric CO_2, typical of this period, may well be implicated in the development of this new mode of carbon fixation [see *Osborne and Beerling*, 2006 for a review]. The spread of C_4 plants is indicated in the stratigraphic signature of carbon isotope ratios preserved in ancient rocks. During photosynthesis the Rubisco enzyme (which evolved in the Precambrian) strongly discriminates in favor of the lighter stable isotope of carbon ^{12}C, while the C_4 carbon fixation still discriminates in favor of ^{12}C, but much less effectively. This results in a marked contrast in the $\delta^{13}C$ signature of organic materials between C_3 and C_4 plants, and this signature is evident, though faint, in carbon preserved in fossil soils from 23 million years ago, with a more significant signature in the sedimentary record from 9 million years ago, during the late Miocene. This was followed by an abrupt rise in the domination of C_4 grasses in the terrestrial biosphere that has been linked to regional effects in climate [*Osborne and Beerling*, 2006; *Edwards et al*., 2010].

These events do not define chronostratigraphic boundaries within the Oligocene and Miocene series of the Cenozoic Era (strictly speaking "Erathem"), which are dependent on first or last occurrences of marine microfossils for their definition — biological events that can be readily correlated around the globe, and mark effectively isochronous surfaces. Nevertheless, the earliest origins of the C_4 mechanism in grasses suggest the early Oligocene, whilst the first stratigraphic signatures of C_4 plants approximate to the early Miocene (its Aquitanian Stage). The widespread appearance of C_4 plants can be seen as a signature of the late Miocene (within its Tortonian and Messinian stages). This stratigraphic signature of C_4 plants is important in identifying a mechanism that is responsible for around 20%–30% of carbon fixation in plants [*Osborne and Beerling*, 2006 and references therein] and, more notably from an Anthropocene perspective, 30% of global agricultural grain production [*Steffen et al*., 2004].

5.2. The Impact of Humans in the Stratigraphic Record

In this section, we consider whether fundamental changes to the biosphere made by humans, and the resulting physical stratigraphic record in fossils, trace fossils, technofossils [*Zalasiewicz et al*., 2013, 2014b], and chemical signatures, provide a possible datum for a chronostratigraphic boundary for the base of an Anthropocene Series, as is the case for example with *Treptichnus pedum* at the base of the Cambrian System [*Landing et al*., 2013]: or, whether they are more useful as ancillary data, as in the case of the evolution of

C_4 plants during the Miocene Epoch. The fundamental logic here is that humans have changed the flow of energy through the global ecosystem in ways that produce a recognizable stratigraphic signal.

The stratigraphical signal of significant human influence is indicated by the earliest stone tools, manufactured by hominins some 2.6 million years ago [*Semaw et al*., 2003; Figure 4], though there are signs of tool usage some 800,000 years earlier [*McPherron et al*., 2010]. This early record is scant and limited to Africa, but becomes progressively more global as early *Homo* migrated out of Africa, culminating in the near-global signal of stone tools from *Homo sapiens* by the late Epi-Paleolithic some 15,000–10,000 years ago (Figure 5). Because this record of stone tool technofossils is predicated on the pattern of human migration, its stratigraphical signal remains highly diachronous (and sparse), and it is therefore not optimal for defining an Anthropocene Series boundary. It is therefore more like the Miocene stratigraphical signal of C_4 plants than the Cambrian example of *Treptichnus pedum*. The more recent (Holocene) correlation of humans with forest clearance and the incidence of fire [e.g., *Power et al*., 2008; *Kaplan et al*., 2010] is also diachronous [*Marlon et al*., 2010], though there are "peak" signals, such as the accumulation of black carbon in Greenland ice at 1900 [*Marlon et al*., 2008], that reflect the human impact on biomass burning toward the end of the 19th century. The spread of agriculture, writing, urbanization, literature, technological advances, states, etc., are also diachronous, though on a finer timescale than Paleolithic events (Figure 6). These developments are associated with a gradual yet increasingly rapid build-up of anthropogenically modified strata, marked by inclusions of novel materials (ceramics, glass, concrete, metal alloys, plastics, etc.) unprecedented in the rest of the geological record. Although underlying strata contain remains of organisms whose morphology was subject to forces of natural selection, anthropogenic strata also contain remains of domesticated animals and plants that were subject to human as well as natural selection—indications of a major shift in patterns of biomass production and consumption. This diachronous evidence does not provide a globally synchronous boundary as such, but it does provide an abundance of signals (such as first appearances of specific types of novel materials in physical stratigraphic contexts), which, without being precisely synchronous, could be used together with other evidence as part of the basis for a chronostratigraphic boundary. It is therefore important in any discussion of where that timeline should be placed [*Edgeworth et al*., 2015].

Global and geologically abrupt signals that result from changes in how humans have appropriated fossil fuel energy (Figure 1), though still diachronous on a fine timescale (of a few years), might be useful to help characterize the base of the Anthropocene within a chronostratigraphically defined reference section (Global Boundary Stratotype Section and Point or GSSP). These could include: the appearance of novel organic polymers and materials (plastics) formed from contemporary or fossil hydrocarbons [*Zalasiewicz et al*., 2016]; the emissions resulting from the liberation of fossil NPP from fossil fuels, in the form of hydrocarbons, such as black carbon and spheroidal carbon particles preserved in sediments [*Rose*, 2015]; the great number of polyaromatic derivatives [e.g. *Olajire et al*., 2005, *Pies et al*., 2007; *Vane et al*., 2014]; the records of elevated carbon dioxide, methane and nitrogen oxide (NO_x) concentrations found in air bubbles preserved in glacial ice or expressed via a marked change in stable carbon isotope ratios; or elevated levels of nitrates and phosphates found in soils or flushed into lake sediments, derived from greatly increased use of fertilizers, and impacting even sites far-removed from direct, point-source, anthropogenic activities [*Holtgrieve et al*., 2011; *Wolfe et al*., 2013; *Waters et al*., 2016]. Signals associated with airborne particulates and atmospheric compositional changes are particularly advantageous for correlation as they disperse rapidly across the planet and are evident in many quite different environments.

As Green Revolution technologies are also predicated on high-energy input, this has left a corollary signal in the human appropriation of fossil NPP. As a result of hyper-fertilization, the amount of reactive nitrogen at the Earth's surface has been approximately doubled, a perturbation of the nitrogen cycle that may be the greatest since Proterozoic times [*Canfield et al*., 2010], and one that has left a widespread stratigraphic signal in the form of changed ratios of stable nitrogen isotopes in organic matter [*Holtgrieve et al*., 2011; *Wolfe et al*., 2013], with similar perturbations of the phosphorus cycle, involving a massive transfer of phosphates from rock strata to surface soil [*Steffen et al*., 2015]. Overspill from this hyper-fertilization has spread, via river input, into the marine realm where, in the last half-century, it has converted some 250,000 km^2 of coastal zone worldwide into seasonal "dead zones" where sinking and decay of fertilizer-fed plankton blooms lead to oxygen deficits on the sea floor and mass die-off of metazoan communities [*Diaz and Rosenberg*, 2008],

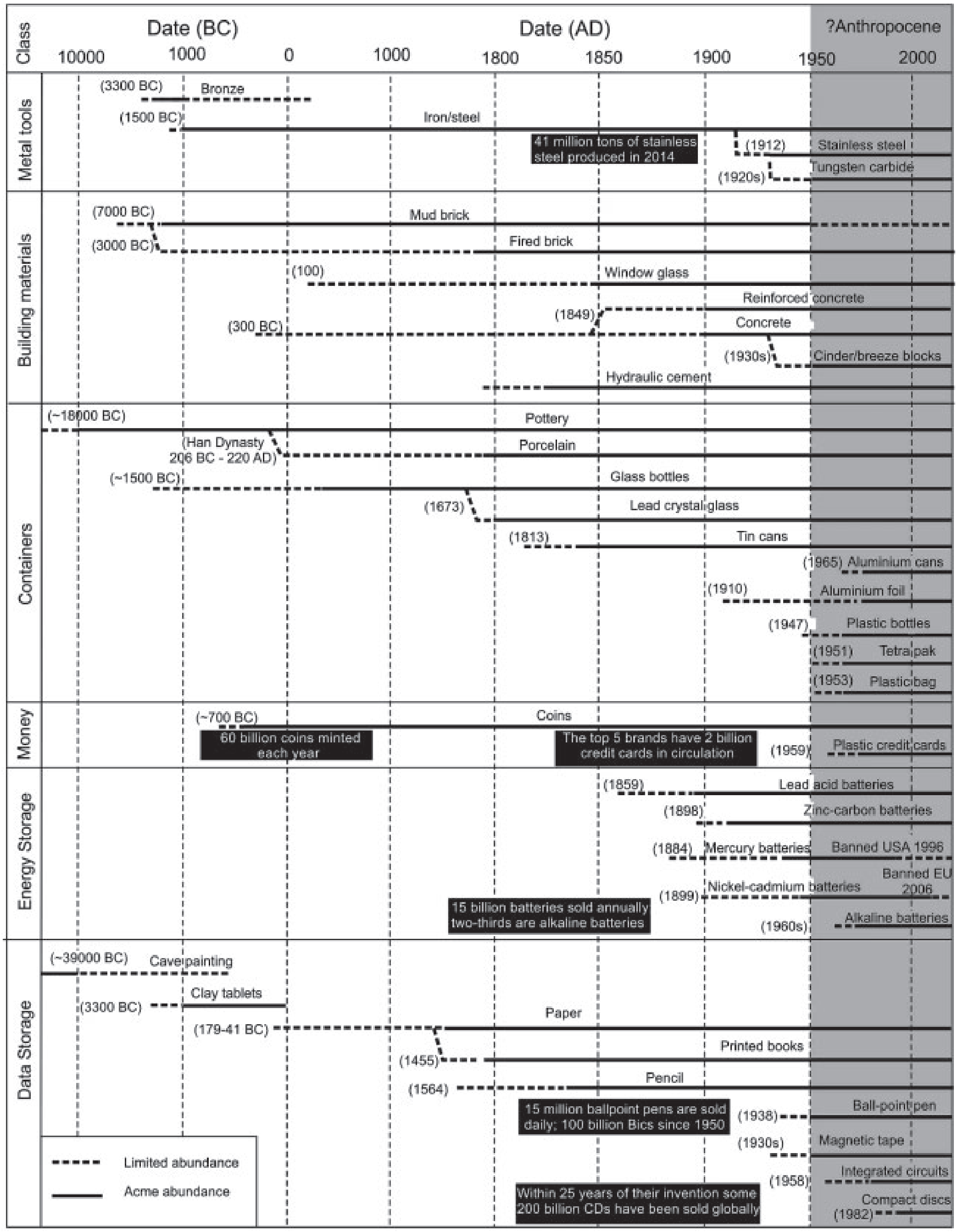

Figure 6. Selected human cultural and technological innovations from the late Paleolithic culture to present signaled by technofossils that identify diverse changes in patterns of human energy production and consumption, including: the development of metals that ultimately provided the means for large scale appropriation of energy (via, for example, combined harvesters, or dairy farms); building materials for storing and distributing the energy of production, and for housing large populations of farm animals and humans; systems of chemical energy storage that ape chemoautotrophic systems in nature; containers as a way of measuring, quantifying and disseminating production; money as a means of facilitating the exchange of production (for example, over 35 billion US federal reserve notes in circulation, and 113 billion US coins circulating, figures from http://www.coindesk.com/microscope-real-costs-dollar/); and data-storage originally as a means of disseminating inventories of production, but ultimately for disseminating methods and ideas for enhancing production.

a phenomenon which is being amplified by the warming and increased stratification of ocean water as climate changes [*Altieri and Gedan*, 2014].

The perturbed sedimentary lithofacies of dead zones and of trawled areas, and the paleontological consequences of a truncated marine food web, will likely leave detectable physical stratigraphical signals, particularly evident from around the mid-20th century, though the scientific assessment of these signals is only just beginning [*Ramirez-Lodra et al*., 2011; *Puig et al*., 2012; *Kidwell*, 2015]. The rise in atmospheric and hence oceanic CO_2 following from the consumption of fossil fuels is also likely to lead, as it did at the Paleocene-Eocene boundary (some 55 million years ago), for example, to a significant shoaling of the Carbonate Compensation Depth (CCD), as the oceans increase their level of acidity, leading to the demise of deep sea carbonate sediments and their associated benthic faunas [*Zachos et al*., 2008]; this will lead to a widespread and globally synchronous physical stratigraphic signal across the deep ocean floor, like that at the Paleocene–Eocene series boundary when the CCD shoaled by more than 2 km and many benthic calcareous faunas became extinct.

6. Conclusions

The history of production and consumption of biomass on Earth has an imperfect geological record, but shows a pattern of increasing complexity over time. Some of the most significant changes include the advent of photosynthesis leading to a global biosphere and enhanced production; the development of tissues for specific functions in animals leading to the complex trophic structures of the Phanerozoic Eon with no single species dominating either marine or terrestrial food webs; and the development of a complex terrestrial biosphere in which plants — as primary producers — comprise the largest standing biomass unit on land. Significant changes to patterns of production or consumption during the evolution of the biosphere have nevertheless maintained a long-term stable relationship between producers and consumers.

A recent stage of evolution may be associated with the influence of humans, who are increasingly refashioning the biosphere (of which they are part) at every level, from the global [*Rockström et al*., 2009; *Barnosky et al*., 2012; *Waters et al*., 2016] to the microscopic altering of the genome [*Ledford*, 2015], with largely unknown consequences. This human enterprise has left a distinctive physical stratigraphic signal of impacts on production, use of fossil fuel to augment production, and on the consumption of biomass by humans. The beginnings of this process are identified by stone tools in the Paleolithic culture, unfolding into a clear signal of energy production that makes possible manufacturing and consumption of goods, reflected in a diachronous signal of technofossils and human bioturbation across the planet, in tandem with human migration over the millennia, and with significant and almost isochronous stratigraphical signals by the 20th century.

By the mid-20th century, the geological record no longer records mere human presence and localized influences on various environments. Instead, the mid-20th century approximates the initiation of significant human influence upon several key global biogeochemical cycles, with attendant influences on the climate system. These stratigraphic considerations are a valuable resource as tracers of the human influence on the biosphere, which is growing with an increasing human population whose per capita energy consumption and resource use is rising rapidly, and in addition may help in qualifying or establishing a formal Anthropocene Series as a geological event. In sum, human changes to production and consumption are so extensive that it is reasonable to suggest that the biosphere has made one of the greatest transitions in the history of life and entered a new stage of its evolution.

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