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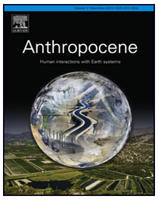

Short communication

Fire and human evolution: The deep-time blueprints of the Anthropocene

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A B S T R A C T

The scale of carbon emissions associated with industrial activity and land clearing is leading to a rise in atmospheric greenhouse gases (GHG) at a rate unprecedented in the Cainozoic record, excepting events triggered by global volcanic eruptions, large asteroid impacts and methane release. Such an evidence is leading to attempts at classification of a new geological era—the Anthropocene. The era has been defined in terms of the onset of the modern industrial age and its acceleration since about 1950. On one hand, it could be from the onset of Neolithic agriculture and gradual rise in carbon dioxide (CO_2) since ~6000 years ago and methane since ~4000 years ago. On the other hand, it may be an amalgamation of factors in an era referred to as the Palaeoanthropocene. This paper suggests the defining point leading to the Anthropocene and subsequently the 6th mass extinction of species hinges on the mastery of fire and thereby the magnification of energy output and entropy in nature over which, in the long term, the species has no control. The discoveries of ignition of fire and its transfer have rendered *Homo* a unique genus from the minimum age of >1.8 million years (Ma) ago, regarded as a turning point in biological evolution and termed here Early Anthropocene. The onset of the Neolithic, allowed by stabilization of the Holocene climate, is referred to as the Middle Anthropocene, while the onset of the industrial age since about 1750 AD is referred to as the Late Anthropocene.

1. A flammable biosphere

During much of Earth's history oxygen-poor levels of the atmosphere and oceans, as low as 10^{-4} bars at 3.4 billion years ago (Krull-Davatzes et al., 2010) restricted life to methane metabolizing bacteria, sulphur bacteria, cyanobacteria and algae. From about ~700 million years-ago (Ma), in the wake of global glaciation, elevated oxygen concentrations of cold water allowed synthesis of oxygen-binding proteins, leading to development of multicellular animals, followed by proliferation of life in the '*Cambrian explosion*' (Gould, 1989) about 542 Ma. The emergence of land plants in the late Silurian (~420 Ma), the earliest being vascular plants (*Cooksonia*, *Baragwanathia*), and later Cycads and Ginkgo in the Permian (299–251 Ma) (Beerling, 2007), combined with the rise in photosynthetic oxygen above 13%, set the stage for land fires (Glasspool et al., 2004; Scott and Glasspool, 2005; Bowman et al., 2009). Decaying vegetation and fires deposited many parts of the land with layers of carbon located in soils, bogs, methane hydrate and methane clathrate deposits. The combination of surface carbon with the atmospheric oxygen emitted by photosynthesis, resulted in flammable land surfaces. Burial of carbon in sediments has stored the carbon over geological periods—pending the arrival of *Homo sapiens*.

Prior to the ignition of fire by Humans wildfires were triggered by lightening, incandescent fallout from volcanic eruptions, meteorite impacts and spontaneous combustion of peat. The role of extensive fires during warm periods, including the Silurian–Carboniferous (443–299 Ma) and the Mesozoic era (251–65 Ma), is represented by charcoal remains whose origin as residues from fires is identified by their high optical refractive indices. Permian (299–251 Ma) coals formed during a period when atmospheric oxygen exceeded 30%, a level at which even moist vegetation becomes flammable, may contain concentrations of charcoal as high as 70% (Glasspool et al., 2004; Scott and Glasspool, 2005; Bowman et al., 2009).

2. A fire species

The appearance of a primate species that has learnt to ignite fire has led to a turning point in the Pleistocene. In terms of Darwinian evolution for the first time the carbon-rich biosphere interfaced with an oxygen-rich atmosphere could be ignited by a living organism, creating a blueprint for extreme rise in entropy in nature and a mass extinction of species. As a direct consequence of the discovery of fire, according to Wrangham (2009) the cooking of meat and therefore enhanced consumption of proteins allowed a

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major physiological development into tall hairless humans—*Homo ergaster* and *Homo erectus*. The utilization of fire has thus constituted an essential anthropological development, with consequences related to bipedalism, brain size and the utilization of stone tools. Partial bipedalism, including a switch between two and four legged locomotion, is common among organisms, cf. bears, meerkats, lemurs, gibbons, kangaroos, sprinting lizards, birds and their dinosaur ancestors. *Homo sapiens*' brain mass of 1300–1400 g is lesser than that of whales (brain ∼6 kg; body ∼50,000 kg) and elephants (brain ∼7 kg; body ∼9000 kg). *Homo* has a brain/body weight ratio of 0.025, higher than elephants and whales, similar to mice and lower than that of birds (∼0.08), whose high neocortex to brain ratio (Dunbar index) (Dunbar, 1996) is related to their high sociability and enhanced communications. Many organisms use tools and construct articulate structures, examples being the elaborate architecture of termite nests, bee hives, spider webs and beaver dams and the use of rudimentary tools by chimpanzees and orang-utans. Examples of sophisticated language among animals include the bee dance, bird songs and the echo sounds of whales and dolphins, possibly not less complex than the language of original prehistoric humans.

Where humans witnessed fire from lightening and other sources, ignition was invented by percussion of flint stones or fast turning of wooden sticks associated with tinder, the process being developed once or numerous times in one or many places (Table 1). Likely, as with other inventions, the mastery of fire was driven by necessity, under the acute environmental pressures associated with the descent from warm Pliocene climate to Pleistocene ice ages (Chandler et al., 2008; de Menocal, 2004). Clear evidence for the use of fire by *H. erectus* and *Homo heidelbergensis* has been uncovered in Africa and the Middle East. Evidence for fire in sites as old as 750 kyr in France and 1.4 Ma in Kenya are controversial (Stevens, 1989; Hovers and Kuhn, 2004). Possible records of a ∼1.7–1.5 Ma-old fire places were recovered in excavations at Swartkrans (South Africa), Chesowanja (Kenya), Xihoudu (Shanxi Province, China) and Yuanmou (Yunnan Province, China). These included black, grey, and greyish-green discoloration of mammalian bones suggestive of burning. During the earliest Palaeolithic (∼2.6–0.01 Ma) mean global temperatures about 2 °C warmer than the Holocene allowed human migration through open vegetated savannah in the Sahara and Arabian Peninsula.

The transition from the late Pliocene to the Pleistocene, inherent in which was a decline in overall temperatures and thus a decrease in the energy of tropical storms, has in turn led to abrupt glacial-interglacial fluctuations, such as the Dansgaard-Oeschger cycles (Ganopolski and Rahmstorf, 2002), requiring rapid adaptation. Small human clans responded to extreme climate changes, including cold fronts, storms, droughts and sea level changes, through migration within and out of Africa. The development of larger brain size and cultural adaptations by the species *H. sapiens* likely signifies the strong adaptive change, or variability selection, induced by these climate changes prior to the 124,000 years-old (124 kyr) (1000 years to 1 kyr) Eemian interglacial, when temperatures rose by ∼5 °C to nearly +1 °C higher than the present and sea level was higher by 6–8 m than the present.

Penetration of humans into central and northern Europe, including by *H. heidelbergensis* (600–400 kyr) and H. *neanderthalensis* (600–30 kyr) was facilitated by the use of fire for warmth, cooking and hunting. According to other versions (Roebroeks and Villa, 2011), however, evidence for the use of fire, including rocks scarred by heat and burned bones, is absent in Europe until around 400 kyr, which implies humans were able to penetrate northern latitudes even prior to the mastery of fire, possibly during favourable climatic periods. A widespread use of fire in the late Palaeolithic is indicated by charred logs, charcoal, reddened areas, carbonized grass stems and plants, and by wooden implements which may have been hardened by fire. Robust evidence exists for a widespread use of fire from about 125 kyr.

Wrangham (2009) interpreted the increase in brain size and the drop in tooth size of *H. erectus* (brain – 900–1200 cm^3) at 1.9–1.7 Ma, relative to *H. habilis* (brain – 500–900 cm^3), as a consequence of cooking of meat and thereby easier digestion of proteins, relieving early humans from energy-consuming chewing and allowing an increase in the brain blood supply. However, to date little or no confident evidence exists for a mastery of fire at that time. More reliable evidence for the use of fire comes from the Bnot Ya'akov Bridge, Israel, where between 790–690 kyr *H. erectus* or *H. ergaster* produced stone tools, butchered animals, gathered plant food and controlled fire (Stevens, 1989). At that stage glacial/interglacial cycles accentuated to ±6 °C and sea level fluctuations to near ±100 m. The intensification of glacial-interglacial cycles controlled intermittent dispersal of fauna, including humans, between Africa, the Middle East, southern and south-eastern Asia (Dennell and Roebroeks, 2005).

Some of the best information on prehistoric fires includes the burning strategies used by native people in Africa, North America and Australia (Pyne, 1982, 1995; Russell, 1983; Lewis, 1985; Kay, 1994; Laris, 2002; Obaa and Weladjib, 2005; Stephens et al., 2007; Bird et al., 2008; Gammage, 2011; Roebroeks and Villa, 2011; Huffman, 2013). Aboriginal '*firestick farming*' associated with maintenance of small-scale habitat mosaics increased hunting productivity and foraging for small burrowing prey, including lizards. This led to extensive habitat changes, possibly including the extinction of mega-fauna (Miller et al., 2005). Maori coloniza-

Table 1
Prehistoric sites containing evidence or possible evidence of human use of fire.

Chesowanja Kenya	1.42 ± 0.07 Ma K–Ar age of overlying basalt	Discoloured clay aggregates intermingled with Oldowan lithics and fauna. Magnetic susceptibility studies	Gowlett et al., 1981. Nature 294:125–129.
Koobi Fora and Middle Awash, Kenya	∼1.5 Ma	Burnt discoloured sediment patches based on thermo-luminescence	Bellomo, R., 1994. J. Hum. Evol. 27:173–195. Clark, J.D., Harris, J.W.K., 1985. Afr. Arch. Rev. 3, 3–27.
Wonderwerk Cave, Kuruman Hills. Western Transvaal, South Africa.	1.0 Ma	Fourier transform infrared microspectroscopy (mFTIR) analyses of intact sediments indicating burned bone and ash plant remains	Berna et al., 2012. www.pnas.org/cgi/doi/10.1073/pnas.1117620109
Swartkrans, Gauteng, South Africa	1.0–1.5 Ma	Burnt bones, charcoal	Brain, C.K., 1993. Nature 336, 464–466.
Gesher Benot Ya'akov, Jordan Valley	0.7–0.8 Ma	Pot-lid fractures (planoconvex stone flakes–burnt microdebitage) Thermoluminescence. charred wood, seeds, and grains.	Goren-Inbar, N., et al., 2004. Science, 304, 725–727.
Zhoukoudian cave, China	0.6 Ma	Burned bones associated with burned flint, Wood ash residues	Weiner, et al., 1998. Science 281, 251–253.
Qesem Cave, Israel	0.38–0.2 Ma	Burnt bone, heated soil, 10–36% of identified bone specimens show signs of burning, reaching 500 °C	Karkanas, P., et al. 2007. J. Hum. Evol. 53, 197–212.

tion of New Zealand 700–800 years-ago led to loss of half the South Island's temperate forest (McGlone and Wilmshurst, 1999). These practices intensified in some regions upon European colonization, with extensive land cultivation and animal husbandry, whereas in other regions, including North America and Australia, forests were allowed to regrow, an issue subject to current debates (Gammage, 2011; Bowman et al., 2011, 2013).

3. Fire and entropy

The colonization of land by plants in the early Palaeozoic (Rothwell et al., 1989), ensuing in the formation of carbon-rich layers and in an enhanced release of photosynthetic oxygen, set the stage for extensive land surface fires. Plants utilize about one thousandth of the approximately 5.7×10^{24} J of solar energy annually irradiated to the earth's surface, absorbing 3×10^{21} J/year to fix large amounts of CO_2 (2×10^{11} tonne/year) (Hall, 1979). Oxygenation reactions through fire and by plant-consuming organisms, including humans, enhance degradation and entropy. The harnessing of fire by humans, elevating the species' oxygenating capacity by many orders of magnitude through utilization of solar energy stored in plants by photosynthesis (Kittel and Kroemer, 1980), has raised planetary entropy to levels approaching those of global volcanic events and asteroid impact events. Through Earth history, these episodic events abruptly elevated atmospheric concentrations of greenhouse gases and aerosols at rates to which habitats and species could not adapt, leading to mass extinction of species (Keller, 2005; Glikson, 2005, 2010, 2013). The effect of humans-generated combustion on nature is tracking towards a similar order of magnitude. Thus, human respiration dissipates 2–10 calories per minute, a camp fire covering one square metre releases approximately 180,000 calories per minute, and the output of a 1000 MW/h power plant expends some 2.4 billion calories per minute, namely some 500 million times the mean energy level of individual human respiration.

The phenomenon of life, magnified in complex technological civilizations focused on cities, entails local and transient increases in potential energy, or anti-entropy. This, however, comes at the expense of an increase in energy-dissipation, namely a rise in entropy, in cleared, degraded and depleted environments from which urban centres derive their resources. Since the industrial revolution oxidation of fossil carbon relics of ancient biospheres has increased the release of energy stored in plants and plant remains by many orders of magnitude. This is represented by the rise in carbon emissions from landscape and biomass burning by 2–4 billion tonnes carbon per year, and from fossil fuel combustion by 7.2 billion ton per year (Bowman et al., 2009). By the Twenty-first century the combined anthropogenic carbon release from fossil fuel combustion and fires is rising above 9.2 billion tonnes per year, with far reaching consequences for the level of greenhouse gases and thereby of temperatures and climate state of the atmosphere-ocean-cryosphere-biosphere system.

4. The Anthropocene

The dawn of the Neolithic owes its origin to the stabilization of the Holocene climate about ~8 kyr allowing cultivation of crops, animal husbandry and related crafts—pottery and smelting of metals. Extensive burning and land clearing during the Holocene magnified entropy, where the extent of biomass burning, as indicated by residual charcoal deposits, has reached levels as high as from the combustion of fossil fuels during the first part of the 20th century (Bowman et al., 2009). Ruddiman (2003) defines the onset of an Anthropocene from a rise in CO_2 from ~6000 years-ago when levels rose from ~260 ppm (to ~280 ppm about 1750 AD) and of methane from ~4000 years-ago when levels rose from 550 ppb (to ~700 ppb about 1750 AD), consequent on land clearing, fires and cultivation. Kutzbach et al. (2010), comparing Holocene temperature variations with those of earlier interglacial periods, estimates the rise of anthropogenic greenhouse gas levels during the Holocene has prevented a decline in temperatures into the next glacial cycle by as much as ~2.7 °C. By contrast Crutzen and Stoermer (2000) and Steffen et al. (2007) define the onset of the Anthropocene at the dawn of the industrial age in the 18th century or from the acceleration of climate change from about 1950. According to this classification the mid-Holocene rises of CO_2 and methane are related to a natural trend, as based on comparisons with the 420–405 kyr Holsteinian interglacial (Broecker and Stocker, 2006). Other factors supporting this interpretation hinge on the CO_2 mass balance calculation, CO_2 ocean sequestration rates and calcite compensation depth (Joos et al., 2004). Foley et al. (2013) define the Anthropocene between the first, barely recognizable anthropogenic environmental changes, and the industrial revolution when anthropogenic changes of climate, land use and biodiversity began to increase very rapidly. Although the signatures of Neolithic anthropogenic emissions may be masked by natural variability, there can be little doubt human-triggered fires and land clearing contributed to an increase in greenhouse gases.

A definition of the roots of the Anthropocene in terms of the mastery of fire from a minimum age of >1.8 million years ago suggests a classification of this stage as "*Early Anthropocene*", the development of agriculture as "*Middle Anthropocene*" and the onset of the industrial age as "*Late Anthropocene*", as also discussed by Bowman et al. (2011) and Gammage (2011). Since the 18th century culmination of the late Anthropocene saw the release of some >370 billion tonne of carbon (GtC) from fossil fuels and cement and >150 GtC from land clearing and fires, the latter resulting in decline in photosynthesis and depletion of soil carbon contents. The total amounts to just under the original carbon budget of the atmosphere of ~590 GtC. Of the additional CO_2 approximately 42% stays in the atmosphere, which combined with other greenhouse gases led to an increase in atmospheric energy level of ~3.2 W/m^2 and of potential mean global temperature by +2.3 °C (Hansen et al., 2011). Approximately 1.6 W/m^2, equivalent to 1.1 °C, is masked by industrial-emitted sulphur aerosols. Warming is further retarded by lag effects induced by the oceans (Hansen et al., 2011). The Earth's polar ice caps, source of cold air vortices and cold ocean currents such as the Humboldt and California current, which keep the Earth's overall temperature in balance, are melting at an accelerated rate (Rignot and Velicogna, 2011). Based on palaeoclimate studies the current levels of CO_2 of ~400 ppm and of CO_2-equivalent (CO_2 + methane + N_2O) of above >480 ppm, potentially committing the atmosphere to a warming trend tracking towards Pliocene-like conditions.

5. Conclusions

It is proposed the Anthropocene is defined in terms of three stages:

Stage A. "*Early Anthropocene*" ~2 million years ago, when fire was discovered by *H. ergaster*.
Stage B. "*Middle Anthropocene*" when extensive grain farming developed.
Stage C. "*Late Anthropocene*" with the onset of combustion of fossil fuels.

Stage A constitutes the geologically fundamental step without which neither stage B nor stage C are likely to have occurred. The long term consequences on a geological time scale (Berger and Loutre, 2002; Moriarty and Honnery, 2011), may lead to a change in the rhythm of glacial-interglacial cycles. It would take a species possessing absolute wisdom and total control to prevent its own inventions from getting out of hand.

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