



# Engineering the Anthropocene: Scalable social networks and resilience building in human evolutionary timescales

The Anthropocene Review

2017, Vol. 4(3) 199–215

© The Author(s) 2017

Reprints and permissions:

sagepub.co.uk/journalsPermissions.nav

DOI: 10.1177/2053019617742415

journals.sagepub.com/home/anr



Tim Fox,<sup>1</sup> Matt Pope<sup>2</sup> and Erle C Ellis<sup>3</sup>

## Abstract

The Anthropocene represents the emergence of human societies as a ‘great force of nature’. To understand and engage productively with this emergent global force, it is necessary to understand its origins, dynamics and structuring processes as the long-term evolutionary product of human niche construction, based on three key human characteristics: tool making, habitat construction and most importantly: social network engineering. The exceptional social capacities of behaviourally modern humans, constituting human ultrasociality, are expressed through the formation of increasingly complex and extensive social networks, enabling flexible and diverse group organisation, sociocultural niche construction, engineered adaptation and resilience building. The human drive towards optimising communication infrastructures and expanding social networks is the key human adaptation underpinning the emergence of the Anthropocene. Understanding the deep roots of human ultrasocial behaviour is essential to guiding contemporary societies towards more sustainable human–environment interactions in the Anthropocene present and future. We propose that socially networked engineered solutions will continue to be the prime driver of human resilience and adaptive capacity in the face of global environmental risks and societal challenges such as climate change, sea-level rise, localised extreme weather events and ecosystem degradation.

## Keywords

adaptation, anthroposphere, communications, engineering, *Homo sapiens*, human–environment, human evolution, humans, infrastructure, networks, niche construction, resilience, social networks, technology, technosphere, tools, ultrasociality

## Introduction

This paper confronts the Anthropocene crisis narrative with theory and evidence on the deep history of human adaptation, evolution and resilience in the face of major and prolonged environmental,

<sup>1</sup>Independent Consultant, UK

<sup>2</sup>University College London, UK

<sup>3</sup>University of Maryland, Baltimore County, USA

### Corresponding author:

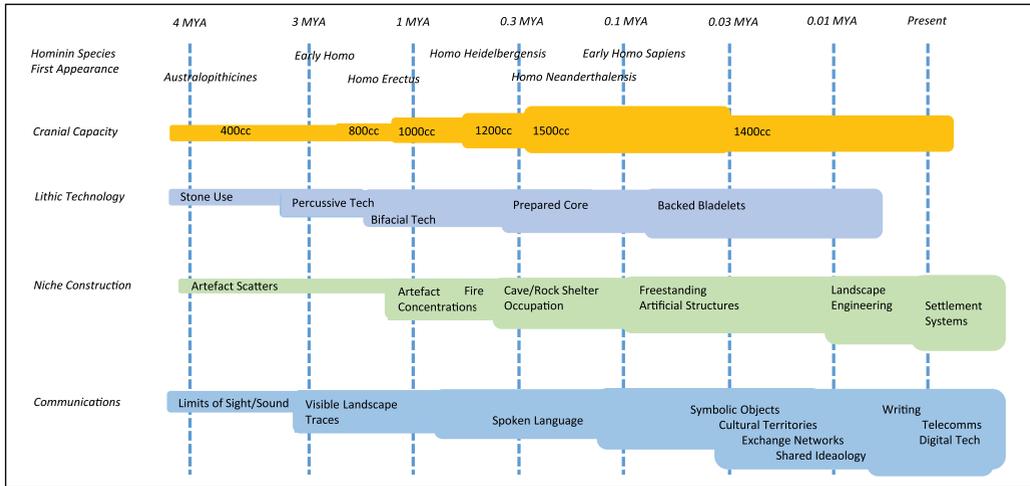
Matt Pope, Institute of Archaeology, University College  
London, 31–34 Gordon Square, London WC1H 0PY, UK.  
Email: m.pope@ucl.ac.uk

social and cultural challenges. We begin with the perspective that the Anthropocene is a useful framework for understanding human–environment interactions on long timescales, as the basis for comprehending the evolution of human societies capable of transforming the Earth System as a whole. This framing is then used to explore the degree to which recent human behaviours that are causing planetary change in fact have deep roots in human evolution. In so doing, we set aside questions of whether the Anthropocene is an appropriate rubric for understanding anthropogenic global change and its timing (e.g. Head, 2014; Lewis and Maslin, 2015; Waters et al., 2016; Zalasiewicz et al., 2012; Malm and Hornborg, 2014), to focus on the premise that framing the human condition and human–environment relationships in deep evolutionary time facilitates a more robust comprehension of what humanity has done, and will likely continue to do, with Earth. Ultimately the goal is a framework within which humans, and their effects on the Earth System, can be understood both through the agency of individuals and, more importantly, as the emergent global force of a social species dependent on cooperation to survive and thrive (Biermann, 2014).

Examining the longer trajectory of human sociocultural evolution may also help to move Anthropocene debates beyond the perpetuation of unhelpful human–nature dichotomies. The geologic history of human alteration of ecosystems and climate promises to frame more nuanced examinations of Anthropocene beginnings that do not lose sight of the continuity between human social and cultural evolution and other natural processes. There is no necessary schism between the human communities of the past, envisaged as living in closer harmony with nature, and the current situation today (Ellis, 2015). Examples and evolutionary frameworks from the prehistoric archaeological record will demonstrate that the building blocks of the Anthropocene can be traced into the Pleistocene and before. It is a perspective that views the contemporary scale and complexity of human systems and their transformation of Earth systems as merely the most recent instantiation of the cultural evolutionary capacities of behaviourally modern humans, both individually and collectively.

If there is no distinct break with the past, why engage with the Anthropocene? In our view, placing humans within the context of planetary and evolutionary timescales enables useful scientific investigation to better understand the past, present, and most importantly, the future possibilities of human social change. It is the only perspective which brings the many trajectories of human societal behaviour into focus in terms of its global development by connecting its deep past, immediate present and possible future pathways. If the Anthropocene remains no more than a debate about the timing of human geologic influence, it will miss the broader opportunity to increase understanding relevant to societal adaptations to environmental change (such as sea-level rise and climate change) and to aid in collective decision making on building resilience to environmental risk and ultimately the efforts of humanity to thrive. If Anthropocene conception can go beyond the notion of a step change in human control of the Earth System, then the record of the human deep past, as provided by the science of archaeology (Boivin et al., 2016; Ellis et al., 2016; Kirch, 2005; Smith and Zeder, 2013), might tell us something about the building blocks on which the structural complexity and exceptional capacities of human society are built and point to pathways towards improving future societal outcomes from different perspectives.

In this paper we review the human evolutionary path with reference to three themes: humans as tool makers, humans as habitat engineers and humans as social network engineers. Against each we examine the role these deep human abilities, maintained culturally and socially, have in shaping the present world. In consequence we bring into focus the unique human drivers of planetary change and their first emergence in evolutionary time among our primate ancestors, other primate species, and extinct *Homo* species. We find that the exceptional global spread and thriving of *Homo sapiens* is the trajectory of an intensely social primate capable of culturally defined group



**Figure 1.** Evolution of increasing scales of social networking indicated by changes in human biology (cranial capacity), lithic technology, niche construction and communications. Increasing scales of human sociocultural niche construction are indicated by changes in material culture and engineered landscapes.

organisation and niche construction at increasing scales (Figure 1). We identify, at the core of this process, the emergence of cooperatively engineered adaptations which enable social resilience building. We propose that communication of information and resources, as ever-expanding networks within and among social groups, has been a key and much overlooked driver of evolutionary trajectories leading to the Anthropocene. Finally, we reflect on the learnings for sustainability and resilience building that can be taken from this fresh perspective and how this new insight might help to meet the unprecedented 21st century challenges of environmental change and increased environmental risk.

## The long engineered drive to a sociocultural niche

### Humans as tool makers

Humans share tool making with a wide range of other organisms crossing not only species but order boundaries (Beck, 1980; Boesch and Boesch, 1990; Emery and Clayton, 2004). Tool use, when defined simply, can be taken to mean the use of an object or material outside of the body of an organism to manipulate another object or aspect of the organism’s environment. Rather than summarise the literature on tool use across all planetary organisms we feel it is useful to focus on how primate, and ultimately, human tool use is developed and maintained within a sociocultural context. Observations of primate tool use indicate that innovation, experimentation and transference of skills within a complex social context makes primate tool use an especially rich, flexible and dynamic adaptation (Matsuzawa, 2001).

Evidence for human tool use can now be pushed back on archaeological grounds to around 3.3 million years (Harmand et al., 2015), with relatively abundant evidence for its presence from 2.6 million years ago (Semaw et al., 2003). However, the simple flake tools which comprise this record already speak of a much deeper evolutionary history. Given the demonstrable presence of tool-use amongst late *Australopithecine* species, or those of the early *Homo* genus, and the fact that we

share the use of tools with other primate species, it is not unreasonable to consider that both the last common ancestor of human and other ape species was also a tool-using organism.

While the evolutionary architecture for tool-use form a range of inherent physical attributes encoded in DNA (e.g. evolution of the hand, eye and shoulder; Marzke, 1997), tool use and the tools themselves do not. Observation of primate behaviour and cross-groups comparisons have shown clearly that primate tool use is a learned behaviour, discovered through experimentation and then disseminated to the wider group through mimicry, observations and directed teaching (especially of infants by adults; Boesch, 1991). The methods of transmission for tool-using behaviour are therefore not genetic, but cultural, the result of social learning (Lycett et al., 2009). Understanding the processes of transmission of cultural concepts such as tools, and their ability to change and mutate over time in response to changing conditions, has led some to invoke Darwinian processes of cultural evolution at work in parallel to biological evolutionary processes (Laland and Brown, 2011; McGrew, 2004; Mesoudi et al., 2006).

We should consider here the pace of tool development and the specificity of cultural evolution relative to biological evolution. In this regard, we observe that *Homo sapiens* now transfer a significant fraction of their 'evolutionary' information outside of DNA (Gillings et al., 2016). This information is acquired in a different manner and reproduced in a sociocultural context; i.e. in the case of tools, humans invent a tool and the ability to make it is transferred down the generations without DNA. *Homo sapiens* improve tools from generation to generation by working with them, such that innovations, or 'improvements', are rarely a result of a random error, as opposed to genetic mutations. In this way the evolution of human capabilities can be many orders of magnitude faster than evolution with DNA (Mesoudi et al., 2006).

But viewing primates, early humans, or behaviourally modern species of *Homo sapiens* as simply cultural tool makers, capable of meeting challenges through innovation and improvement on existing technological solutions, is missing a crucial point. Tools and technology have probably accompanied us on our evolutionary journey for millions of years. Given such immense timescales we need to be aware of the complex relationship between ourselves as organisms and our cultural/technological heritage. The point is that technology, as a key form of cultural adaptation, has had and does have the ability to alter profoundly the trajectory of our evolutionary path; tools and technology from this perspective are supported by humans, but also exist as platforms for cognitive and anatomical development as well as the broadening of the human ecological niche (Ellis, 2015; Henrich, 2015; Richerson and Boyd, 2005).

Excellent examples of this relationship are provided by the earliest Stone Age technologies and their spread across the old world. The first evidence for flaked stone tool use in the archaeological record, from the Lomekwi 3 site, West Turkana, Kenya at 3.3ma, appears to be associated with relatively wooded landscapes and plant processing cannot yet be ruled out as the use to which these early flaked tools were put (Harmand et al., 2015). Claims for bone with stone tool cutmarks have been made for the same time period at Dikika, Ethiopia (McPherron et al., 2010) but it is not until after a million years later in the Oldowan that we get more prevalent evidence for early hominins as scavengers, using the sharp edges of flaked tools and robust percussors to break into and extract protein and fat remaining on carcasses left by predators (Blumenschine et al., 1987). This apparently simple behaviour seemed to be enough to allow effective exploitation of open grassland habitats (Levin et al., 2004), which were at the time becoming more prevalent with a cooling and drying global environment (Bobe and Behrensmeyer, 2004). But longer term, efficient adaptation to these emerging environments seems to have taken more than just tool use and technology, in this regard we start to see the development of an evolutionary trajectory from late Australopithecus, through the early human species *Homo habilis* and *Homo rudolfensis*, towards

a more modern-looking, tall and relatively large-brained human *Homo erectus* by 1.8 million years ago (Leakey et al., 2012). The physical adaptations: increased height, potentially reduced gut size and increased brain size, as well as loss of body hair, are all understandable as adaptations to open environments and possibly a move to a more protein-rich dietary regime (Ungar, 2012). Tool use sits at the heart of this process, allowing access to food in an expanding ecological grassland niche, as well as to a food stuff which, in requiring less gut size to digest, had possibly freed up metabolic energy for human brain growth (Aiello, 1997; Aeillo and Wheeler, 1995).

By this stage, and possibly for millennia before, human evolution had taken place within a culturally evolving social and technological environment (Henrich, 2015; Richerson and Boyd, 2005; Sterelny, 2011). Humans, from their earliest emergence as distinct primate genus, may have been obligate tool-assisted apes, no longer capable of thriving as species without technological solutions to food acquisition and perhaps other aspects of primate life. Humans identified by stone tools and their footprints show up in the cool climates of Northern Europe by 1 million years ago (Parfitt et al., 2010). Here, away from their cradling niche of tropical grassland, but still presumably adapted in biological terms to warm conditions, we find them exploiting pine and birch forests of colder climates with simple stone tool kits. The technology we can observe, the stone tools, must be being used in different ways to adapt to environmental stresses presented by northerly latitudes (White, 2006): potentially skins are being processed for clothing and processes emerging for acquiring animals at earlier stages in the predator food chain, perhaps even through the first expressions of tool-assisted hunting. With an archaeological record so prejudiced against wooden or other organic objects we have to wait until after half a million years to start finding tools such as wooden spears (McNabb, 1989) or bone hammers (Roberts and Parfitt, 1999), but we can predict on the basis of the rapid expansion of humans into new ecological niches and climatic zones, without radical changes to observable anatomy, that it was technological, cognitive and social adaptation rather than physical evolution that was driving adaptation.

The emergence and dispersal of the genus *Homo* has been largely reconstructed from a data set of stone artefacts, plotted in space and time, supplemented by rare but informative fossils remains. But the evidence also shows how important technology, in providing an interface between early *Homo* and the environment, was pivotal in extending hominin range and success. Right from the very early stages of our evolutionary development, the relations of biology and technology were being negotiated in evolutionary time through the medium of sociocultural development. We would argue that what emerged, right up to the present days of the Anthropocene, was a situation where technology became ever more intimately tied and indivisible with the human condition.

### *Early humans as habitat engineers*

But to consider early humans as merely tool makers is to overlook their transformation of the environments they occupied. Biology would suggest that a highly social and technologically capable species might also be expected to engineer ecosystems within the landscapes they occupied from an early stage in their evolution. Allogenic ecosystem engineers are species that modify their environments through their behaviours, either singly or collectively (Jones et al., 1994), and when these altered environments enhance or degrade their survival and reproductive success, this is termed niche construction (Erwin, 2008; Matthews et al., 2014; Odling-Smee, 2003). Examples of niche construction range from the microscopic, such as floating colonies of diatoms, through the tunnelling and nest building of slugs, caterpillars, earthworms and other invertebrates, to environmental alteration by termites, beavers and, of course, primates, all of which

exhibit characteristics of ecosystem engineering and niche construction when their alteration of environments influences their adaptive fitness (Erwin, 2008; Matthews et al., 2014; Odling-Smee, 2003).

Early stone tool accumulations, close to locations where scavenging or hunting opportunities were abundant, have been described as ‘stone caches’, food sharing locales, or formations established through simple rules of strategic discard (Isaac, 1978; Potts, 1988; Schick, 1992). In all these cases, stone tool accumulations indicate a form of niche construction which optimises resources, alters landscapes and potentially changes the later behaviour of hominins in response to encountering the accumulations. Such scatters, from their first appearance, would have effectively encoded information passively in the landscape, reduced risk and enhanced resilience (Pope, 2002; Pope and Roberts, 2005).

Human niche construction has also been invoked for human colonisation of northern latitudes where, without the use of fire, garments and other complex socially learned technologies, humans could not likely survive. Further evidence of engineering is clear in this setting, in the construction of wind breaks and shelters (Bourguignon et al., 2002; Chu, 2009), even though the presence of such structures is not visible archaeologically until after 500,000 years ago. More elaborate shelters, sometimes spectacularly preserved and manufactured from the bone and tusks of large herbivores such as mammoth, are the preserve of sophisticated engineering behaviour by both anatomically modern humans and possibly Neanderthals (Pettitt, 1997). Such shelters, considered alongside the evidence for more complex tent-like structures emerging in the Late Pleistocene, provide a basis for an ability to transform and extend environmental range through niche construction. In combination with the use of fire, present after 500,000 years ago (Roebroeks and Villa, 2011), and the environmental modification of caves (Henry et al., 1996), Late Pleistocene humans can be seen to be engaging in ever more complex patterns of niche construction and resilience building as a part of their behavioural repertoire, including socially learned awareness of local hazards, reducing vulnerability, and enhancing the capacity of communities to cope with shocks in a range of scenarios.

Archaeological evidence in the form of plant and animal remains, charcoal, isotopic records and other legacies demonstrate that human hunter-gatherers long ago engaged in pre- and proto-agricultural land use intensification practices to support larger populations on the same land, including dietary broadening (eating more species, once preferred megafauna were rare or driven extinct), burning vegetation to enhance hunting and foraging success (ecosystem engineering), processing plant and animal foods to enhance nutrient availability (cooking, grinding, etc.), and the propagation of useful species (Boivin et al., 2016; Ellis, 2015; Kirch, 2005; Zeder, 2016). As a side effect, these practices likely facilitated increasing reliance on grasses and other species that would later become crops, putting them on the road to domestication (Fuller, 2010; Zeder, 2016).

Pre-agricultural technologies for ecosystem engineering were much less productive than the agricultural technologies that replaced them. Nevertheless, they still enabled human populations to grow far beyond the capacity of unaltered ecosystems to support them. As populations grew, more intensive land-use practices were adopted to sustain them or populations migrated to areas with less intensive use including uninhabited wildlands. By the early Holocene, hunter-gatherers had expanded their populations across Earth’s terrestrial surface and required early land-use intensification processes to survive and to grow and lived mostly within ecosystems that had already been transformed by their ancestors to enhance their productivity, setting the stage for the rise of agriculture (Ellis, 2015).

Agricultural populations grew more rapidly than those of hunter-gatherers, ultimately replacing them across Earth’s most productive lands. Intensification continued,

with long fallow shifting cultivation replaced by systems with shortened fallows, and eventually continuous cropping enhanced by the plow, irrigation, manuring and other increasingly productive land-use technologies. Intensive agricultural systems gradually proliferated across Earth's most productive lands, supporting densely populated villages and eventually supplying food surplus to growing urban populations. As the demands of urban populations grew, they were sustained by ever-larger scales of farming operations, trading systems, and technological institutions, ultimately leading to the high-yielding industrial 'green revolution' land-use systems by the 1950s and continuing today, sustained by fossil energy and other industrial inputs (Ellis et al., 2013). Industrial technologies, especially mechanisation, have increasingly decoupled human labour from productivity growth in agriculture, thereby allowing the majority of human populations to live in urban areas for the first time. Increasing agricultural intensity has also helped maintain relatively slow increases in human use of land in the face of rapid population growth and progressively richer diets (Ellis et al., 2013).

From this perspective, we can track the evolutionary development of humans through the Middle to Late Pleistocene, into the Holocene and up to the present in terms of sociocultural niche construction, enabled through cooperative ecosystem engineering and embodying characteristics of social learning and resilience. From sustained colonisation of northern latitudes in the old world, and a move towards predation augmented by weapon systems, engineering on a habitat scale appears to form part of the package of human adaptation and facilitated the shift in ecological positioning of the species to both apex predator and dietarily flexible omnivore – an ecological niche of remarkable, if not unprecedented, breadth.

### *Humans as social network engineers*

By the Late Pleistocene humans had already begun to extend further, into Australasia by 50,000 years ago (Aubert et al., 2014) and the Americas by 16,500 years ago (Gobel et al., 2008). Human groups were also becoming more complex in terms of sociocultural structure: with complex shelters exhibiting internal spatial organisation and physical structuring (Iakovleva, 2014), social stratification developing (Trinkhaus et al., 2014), more complex weapon systems (Brown et al., 2012), diversity in diet (e.g. Gutiérrez-Zugasti et al., 2013; Langejans et al., 2012), emergence of ceramics (Svoboda et al., 2014) and elaborate and spatially extensive symbolic systems. The latter are evident by 60,000 years ago in South Africa and South East Asia (Aubert et al., 2014; Henshilwood et al., 2011) and recorded reaching Europe and Asia by 40,000 years ago (d'errico and Stringer, 2011). These symbolic systems, based on repeated behaviours involving, for example, the creation of painted handprints, ceramic female figures, repeated motifs in animal art and abstract geometric design, reveal something profound: Late Pleistocene human groups over widely spaced time and space shared a repertoire of symbolic ideas which can be externalised on the landscape (caves, rock faces) or encoded into objects, sometimes with additional functional uses (Coward and Gamble, 2008).

That this overtly symbolic behaviour emerges with the expansion of anatomically modern humans from Africa has led some authors to consider it the signature of a cognitive threshold being crossed, and to others as the product of larger and more connected human groups using symbolism to organise themselves within space and develop wider sociocultural networks. Trade across social groups, in critical resources such as minerals for tool-making and symbolic prestige goods such as shell beads, also emerges at this time (Nowell, 2010; Sterelny, 2014). We suggest the importance of the latter is that it forms a pre-requisite for enhancing individual, group and community resilience in the face of external shocks that threaten the engineered niche and the challenges of living

in complex social groups (Sterelny, 2011, 2014; Waring et al., 2015), and the emergence of human ultrasociality (Hill et al., 2009). Networks, especially those shown to be based on the long-distance movement of objects or raw material, are key to the emergence of increasing potential for resilience. Such networks are one archaeological trace of the ‘release from proximity’ (Gamble, 1998), which transformed the social trajectory of our genus towards the dislocated but connected world of the modern age.

The social brain hypothesis, which sees human cognitive development being driven by the challenges of thriving in ever-larger social groups or engaging in more complex social behaviour provides a framework for understanding a key driver in human evolution and one shared by our closest relatives, the primates. From its origins as a theoretical body with Aiello and Dunbar (1993), through to elaboration in a human evolutionary context by Gamble et al. (2011), the social brain hypothesis relates aspects of human evolution such as niche broadening, population growth and the emergence of complex social behaviour as underpinning the development of humanity’s unique cognitive abilities.

### *Social upscaling and the Anthropocene*

More effective social grouping, communication and conflict resolution underpin human sociocultural networks, but why might understanding these networks be useful in approaching a concept so widely perceived as geological in domain as the Anthropocene? Given that, as we have outlined, human technological and engineering behaviour are underpinned by social and cultural learning processes, the degree to which innovations, adaptations and hybridisations of human technologies and engineered environments are promulgated and spread is effectively controlled by the speed and effectiveness of our social, information and physical networks (Henrich, 2015; Hamilton et al., 2009). The complexity and scale of human sociocultural networks emerge from population numbers, social structure and our cognitive ability to maintain these networks effectively, creating a nexus of evolutionary drivers which appear to play out over time as a general trend towards increases in the scale and complexity of human societies and their technological capacities (Henrich, 2015). The building blocks for this appear deep in human history, as evident in the indelible traces left on the landscape by our human ancestors, such as the large clusters of stone tools sometimes accompanied by butchered animal bones found in the archaeological record from 2.6 million years ago (Ferraro et al., 2013).

The presence of these larger groupings, which have previously been described as concentrations or even caches of stone artefacts, sometimes away from areas of use (such as lake margins) or within preferred habitat areas (close to springs or sandy bottomed channels) may suggest a more complex behaviour. These groupings may have physically embodied human networks of movement and social-ecological interaction, which left the potential for feedback dynamics in terms that structure the behaviours of our ancestors further. Human systems which now act as a significant global force of nature are far more than simply the ‘artificially’ engineered structures we inhabit or the technologies we interact with (*sensu* Haff, 2014), rather these structures are the material manifestations of the sociocultural niche which has underpinned human societies from their emergence at the end of the Pliocene (Ellis, 2015). The anthroposphere, we argue, has evolutionary roots going back to the origins of our species, even if its effects on the Earth System may have only become glaringly obvious within the last 10,000 years or later.

As the human niche broadened in behaviourally modern humans of the Late Pleistocene, human individuals come to depend more and more on complex networks of social interaction and non-kin

subsistence exchange for their survival and to do this at increasing spatial scales (Kaplan et al., 2009). This increasing dependence on social networks for subsistence has in turn enabled human societies to become increasingly specialised, complex, and hierarchical (Chase-Dunn and Lerro, 2013; Nolan and Lenski, 2010), with individuals specialised in different socially learned productive capacities cooperating with unrelated and often unknown individuals through long-distance exchange networks to accomplish complex tasks. One example is the production of complex tools, which might require the sourcing of different component materials in distant areas, long-distance trade, and their integration into tools by skilled artisans in other areas. By specialisation and exchange, it became possible for human individuals to subsist apart from direct interactions with ecosystems, with needs met through exchange networks of producers (i.e. farmers, fisherman), processors, providers (traders) and potentially many more specialists (tool makers) in complex and dynamic subsistence supply chains (Ellis, 2015).

Ecosystem engineering and social exchange sustained growing populations, and these in turn, required increasingly productive ecosystem engineering practices and more extensive and powerful social networks to sustain them (Ellis, 2015; Hamilton et al., 2009; Kaplan et al., 2009; Smith, 2012). While the social networks of even the most complex hunter-gatherer societies cannot compare in scale or complexity with those of contemporary urban societies, they still served similar social functions in enabling and structuring essential cultural and material exchanges (Brughmans, 2013; Burnside et al., 2012; Hamilton et al., 2009; Kaplan et al., 2009; Ortman et al., 2014). Long before the rise of agriculture and cities, the importance of social networks in structuring the processes of human survival and reproduction were already well established (Brughmans, 2013; Burnside et al., 2012; Cowgill, 2004; Feinman and Garraty, 2010; Hamilton et al., 2009; Kaplan et al., 2009; Ortman et al., 2014).

Over time, as agricultural societies scaled up, the first cities emerged, increasing the concentration of human populations and wealth into central places entirely dependent on social networks to sustain them through trade across large regions (Barbier, 2010; Ortman et al., 2014; Smith, 2004, 2014). The opportunities provided by cities increase with scale, and this has ultimately sustained long-term processes of urbanisation that have shifted populations from the countryside into urban landscapes (Bettencourt, 2013; Klein Goldewijk et al., 2010; Lambin et al., 2001; Smith, 2014). Sustained societal upscaling and the increasing concentration of populations in urban settings dramatically increased the importance of social networks, their governance of global supply chains and their telecoupling of resource demands with ecosystem engineering across the planet (Bruckner et al., 2012; Deville et al., 2016; Grimm et al., 2008; Seto et al., 2012; Zalasiewicz et al., 2014).

## **Scaling the human niche to planetary scale: Ultrasocial engineering**

Tool makers, habitat engineers, social network engineers – humans are fundamentally engineers. But is this character and its associated traits an individual behaviour or is it an emergent social behaviour produced by cultures, social groups and societies? *Homo sapiens* are better at communicating with each other than they are at individual problem solving; the most complex human behaviours are the self-organised emergent behaviours of social groups (Henrich, 2015). The significant majority of human engineering effort in the Holocene has been invested in improving and enhancing communication amongst individual *Homo sapiens*, from forming early paths and activity nodes to settlements, sacred spaces, monuments and markets, and ultimately to the shipping, road, canal, railway, airline, telecommunications and internet infrastructure of today. This becomes even more apparent when thinking about the energy costs and urban infrastructure engineering

required to support ever enhanced levels of human communication and connectivity. We can think here about the accelerating human flow towards becoming an urbanised species, from initially mobile niche acquirer, to the engineering of early settlements and on to today's mega-cities, vast urban conurbations and future 'smart' cities. All of this is a core part of the same social upscaling drive, as in essence urbanisation is fundamentally about coming together to enhance interactivity, communication, and opportunity through economies of scale in materials, cultures, concentration and density (Bettencourt, 2013). Substantial engineering efforts are invested in creating the built environment and the infrastructures that pull them together and sustain them, yet these structures are not the end in themselves.

The unprecedented engineering efforts of *Homo sapiens* have always been and will likely continue to focus on social engagement, communications and exchange. Human engineering of ecosystems, tools, structures and infrastructures is ultrasocial engineering, the construction of a sociocultural niche of increasing scales that has ultimately produced an ever more intensely connected human social niche at global scale at the 'cost' of all else, including environmental degradation, climate change, resource depletion and species extinctions. It is time to stop thinking of the human niche as composed of places (the cave, house, flat, city, nation) and start thinking of it as world systems of interconnected societies across the physical Earth. The human niche is scaled more like a web than a nest.

The individual anatomy, cognition, behaviour and sociocultural frameworks of humans have emerged directly from deep evolutionary processes. This much is easy to grasp. What becomes harder to see is that the contemporary products of human society (modern urbanisation, industrialisation, agriculture, space exploration, digital technology, the internet of things) fundamentally reflect continuity with the deep evolutionary processes underpinning an ultrasocial, tool-assisted, ecosystem engineering population of apes. That the entire engineered context of human societies is, fundamentally, as much a product of evolution as a spider's web, a bird's nest, or more closely, a network of related termite mounds – stretching now across an entire planet. Since prehistory, humans have organised themselves in new and complex ways, increasing the scale of their engineering of land, seas, atmosphere, and of ecology too; the emergence of sociocultural niche construction and social network engineering at ever greater scales through the enabling behaviour of a tool-making ape.

Are the defining characteristics of the Anthropocene then based on a dramatic global shift in the form and scale of these social processes? Or is this global transformation simply the playing out of a deeper evolutionary process? Is the Anthropocene just a recent snapshot of a long-term process of human social upscaling of niche construction from local to global and beyond?

To engage with the Anthropocene is to accept that the human sociocultural niche, dependent on social processes of engineering with deep Pleistocene roots, has now become the 'great force of nature' capable of transforming the biological, atmospheric, oceanic, fluvial and geomorphological systems of planet Earth. To look to the individual and to human agency as a source of species-wide behavioural change is ultimately too limited, as our global force as a species is culturally constructed and structurally maintained by the institutions and engineered environments that support our sociocultural networks. To sustain a thriving human population into the future will depend on sustaining Earth systems that can support increasing food production, healthy settlements, water and energy sourcing and the movement of people, goods and information (Henry and Vollan, 2014). This will require even more robust and connected sociocultural networks to empower social groups and societies to adapt to the challenges of the 21st century and beyond. This will in turn depend on the proven human capacity to continually re-evolve our social, ecological and material

infrastructures and networks so that they build on and with the wider planetary ecology they are now an integral part of.

## Lessons for sustainability and resilience building

If human transformation of the Earth System results from ultrasocial engineering, how can this be directed onto pathways towards more positive outcomes for our species in the Anthropocene? Can an understanding of deeply rooted aspects of human behaviour inform our approach to engineering improvements in human–environment interaction? Taking a deep time view of the evolutionary pathway of *Homo sapiens* enables us to see the key driving characteristic of human sociality, rooted in the need for group survival, translated in the modern world into a fear of missing out on useful/social information and attaining a sense of worth from gaining immediate information and connectivity (Figure 2). At the centre of Anthropocene resilience building is effective communication and social networks – and what we have learnt is that these have always been central to human adaptation and evolution. From this fresh insight we can articulate more clearly focused pathways for advancing human social learning, institution-building, and action in response to environmental risks to humanity and to non-human nature (Isbell and Loreau, 2014; Schmidt, 2017).

Societal resilience to the environmental challenges and risks of the Anthropocene is based on building local social awareness to hazards in a global context, reducing vulnerability, enhancing the capacity of communities to cope with shocks, ensuring critical services recover and function effectively, and learning and sharing knowledge gained to enable communities to bounce back better prepared. Harnessing the overwhelming human driver of social communication should be at the core of strategies and frameworks that aim to build community resilience and/or undertake adaptation of our built environment or engineered infrastructure.

It is anticipated that an additional 3 billion people will migrate into urban landscapes by 2050, taking the proportion of living humans urbanised to over 75% of the total global population, and over 95% of this movement is expected in the developing countries of Asia and sub-Saharan Africa where many will coalesce around existing, environmentally vulnerable sites. These include cities exposed to rising sea levels and coastal storm surges, or sited in low-lying river, lake, estuarine or deltaic plain settings susceptible to fluvial flooding, locations prone to drought or close to geological fault lines inducing earthquake activity. If the resilience of urban dwellers, many of whom will form an increasing trend of ageing populations, is not increased, the incidence of human disasters arising from extreme environmental events will grow along with these expansions. Ultrasocial engineering, connecting people together to solve problems socially, needs to be recognised as the cornerstone for Anthropocene adaptation.

Removing risk entirely, through physical engineering and technological interventions, is often mistaken as the basis of resilience, but this is not at its core. Rather, it is built on a principle that accepts that communities will need to respond to unpredictable events that cannot be planned for fully. It must therefore incorporate uncertainty into preparation activities and, we suggest, harness the characteristic of humans as socially networked allogenic engineers to cope with unknown potential situations. The foundations for building resilience is ensuring that communities, families and individuals are ready to take appropriate actions through planning for interruptions to ‘normal’ services, such as food, water and power, and are well informed both ahead of, and during, extreme events, and that individual and collective learning post-event is harnessed to drive adaptation in the future. Dense and networked human populations, connected together at neighbourhood, urban,

regional and global scales, are already building new forms of community resilience to the unprecedented social and environmental challenges of the Anthropocene.

In the contemporary Anthropocene, with *Homo sapiens* becoming a largely urbanised species, communication is defining ‘community’; social media, smart phones and internet connectivity of people and things are redefining conceptually the notion of ‘communities’, in that an individual’s often limited ‘physical’ community is being replaced or extended by engagement in virtual communities that not only perform the functions of traditional communities, but are potentially more effective in the context of resilience. Is this what should be at the defining core of future ‘smart’ cities? For example, New York City took to social media en masse during Superstorm Sandy in 2012 to instantly share photographs, videos and information that helped people cope with service interruptions and find help where help was needed; 3.5 million tweets were shared in one 24-hour period alone using the hashtag #Sandy. In Jakarta, passive real-time data mining informs communities on flood events, building resilience by improving emergency response and decision making. The opportunity for individuals, social networks, emergency services, non-profits and government agencies to show leadership in resilience building, by pushing against an open door and harnessing the fundamental social drivers of the Anthropocene, embedded deep in our evolutionary history, is clear: continuously strive to both optimise communication and extend human sociocultural networks across the anthroposphere.

## Conclusion

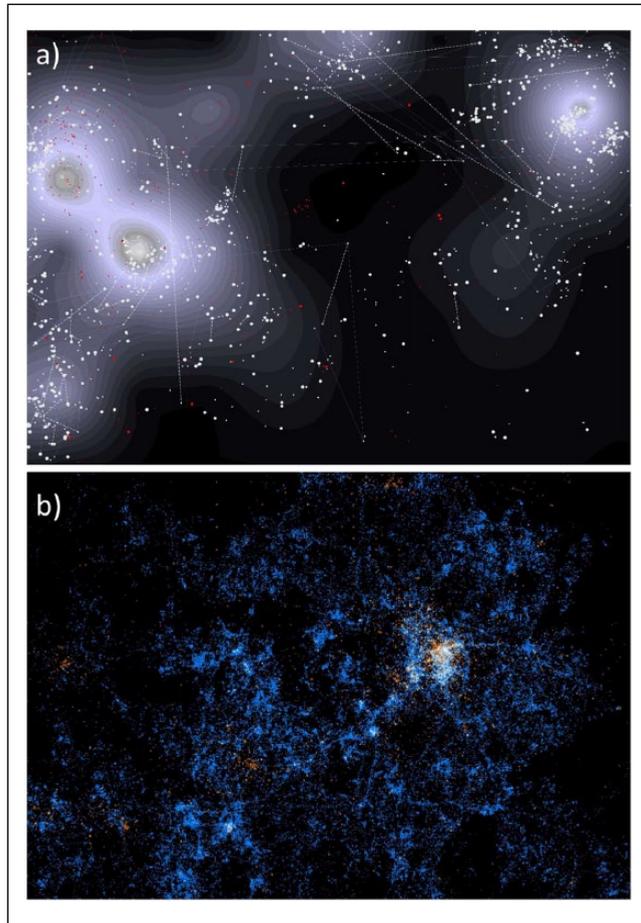
This paper examined processes of human–environment interaction and social change on long evolutionary timescales as a framework for understanding contemporary challenges of sustainability and resilience building in the Anthropocene. Such a framing is, in our view, essential to addressing the unprecedented environmental risks and social challenges of the 21st century, including climate change, sea-level rise, extreme weather events, and an increasingly transformed biosphere.

Resilience-building and human adaptation in the Anthropocene demands broader interdisciplinary understanding of humans as ultrasocial ecosystem engineers, who transform environments to sustain their social world. Current academic and professional silos are not helpful for understanding the human–environmental trajectories of the past or for addressing the unprecedented societal challenges of the Anthropocene. We must ultimately arrive at a perspective where the human world – the anthroposphere – functions as part of an Earth System that now works with us, not without us.

Whatever the scale of Earth’s human transformation or its perceived negative impacts, the Anthropocene is no departure from a ‘natural’ planetary condition. Nevertheless, the evolution of Earth’s first ultrasocial species has caused a new sphere of the Earth System to emerge. While this might represent an unprecedented stage in Earth’s development, it is inherently part of this development, not separate from it. We humans have woven our webs and structures over evolutionary time by building on the same rules that direct all life on this planet. Our newly emerged planetary fluorescence is underpinned by networks of information and communication which afford our populations resilience across unprecedented social scales. It is time to consider how these networks can be extended and improved towards a more sustainable future trajectory for both humanity and non-human nature.

## Funding

The authors have received no external funding in the production of this paper.



**Figure 2.** Shared social spaces, at two very different scales of evolutionary time and space, functioning to build information networks and resilient communities. (a) Shows a Middle Pleistocene horse butchery site from Boxgrove dating to 480,000 years ago. The white and red dots represent fragments of stone artefact and horse bone, respectively, the lines show connections between the artefacts established by refitting and movement of people between activity areas. The contours show intensity of tools using activity at particular locations indicated by micro-artefacts. For a few hours this site, only 12 m across was the scene of intense social interaction and food sharing, the hominin social focus on the site protecting the carcass from other predators (Pope, 2002; Roberts and Parfitt, 1999). (b) Contemporary Kuala Lumpur, Malaysia. The map shows social media sharing across Kuala Lumpur produced and shared by Eric Fischer on Flickr (<https://www.flickr.com/photos/walkingsf/5925795773/in/photostream/>). Red dots are locations of Flickr pictures. Blue dots are locations of Twitter tweets. White dots are locations that have been posted to both. While the spatial scales and duration of interactions are very different, the creation of networks and their potential to build resilience within communities is demonstrable in most aspects of human use of space.

## References

- Aiello LC (1997) Brains and guts in human evolution: The expensive tissue hypothesis. *Brazilian Journal of Genetics* 20.
- Aiello LC and Dunbar RI (1993) Neocortex size, group size, and the evolution of language. *Current Anthropology* 34: 184–193.
- Anton S, Potts R and Aiello LC (2014) Evolution of early Homo: An integrated biological perspective. *Science* 345: 128–142.
- Barbier EB (2010) *Scarcity and Frontiers: How Economies Have Developed Through Natural Resource Exploitation*. Cambridge: Cambridge University Press.
- Beck BB (1980) *Animal Tool Behavior: The Use and Manufacture of Tools by Animals*. Garland STPM Publ.
- Bettencourt LMA (2013) The origins of scaling in cities. *Science* 340:1438–1441.
- Biermann F (2014) The Anthropocene: A governance perspective. *The Anthropocene Review* 1: 57–61.
- Bobe R and Behrensmeier AK (2004) The expansion of grassland ecosystems in Africa in relation to mammalian evolution and the origin of the genus *Homo*. *Palaeogeography, Palaeoclimatology, Palaeoecology* 207(3): 399–420.
- Boesch C (1991) Teaching among wild chimpanzees. *Animal Behaviour* 41(3): 530–532.
- Boesch C and Boesch H (1990) Tool use and tool making in wild chimpanzees. *Folia Primatologica* 54(1–2): 86–99.
- Boivin NL, Zeder MA, Fuller DQ et al. (2016) Ecological consequences of human niche construction: Examining long-term anthropogenic shaping of global species distributions. *Proceedings of the National Academy of Sciences* 113: 6388–6396.
- Bourguignon L, Sellami F, Deloze V et al. (2002) L’habitat moustérien de La Folie (Poitiers, Vienne): Synthèse des premiers résultats. *PALÉO. Revue d’archéologie préhistorique* 14: 29–48.
- Brown KS, Marean CW, Jacobs Z et al. (2012) An early and enduring advanced technology originating 71,000 years ago in South Africa. *Nature* 491(7425): 590–593.
- Bruckner M, Giljum S, Lutz C et al. (2012) Materials embodied in international trade – Global material extraction and consumption between 1995 and 2005. *Global Environmental Change* 22: 568–576.
- Brughmans T (2013) Thinking through networks: A review of formal network methods in archaeology. *Journal of Archaeological Method and Theory* 20: 623–662.
- Burnside WR, Brown JH, Burger O et al. (2012) Human macroecology: Linking pattern and process in big-picture human ecology. *Biological Reviews* 87: 194–208.
- Chase-Dunn CK and Lerro B (2013) *Social Change: Globalization from the Stone Age to the Present*. Boulder, Colorado, USA: Paradigm Publishers.
- Chu W (2009) A functional approach to Paleolithic open-air habitation structures. *World Archaeology* 41(3): 348–362.
- Clarke A (2000) *Natural Born Cyborgs?* Edge.
- Coward F and Gamble C (2008) Big brains, small worlds; Material culture and the evolution of the mind. *Philosophical Transactions of the Royal Society B* 363(1499): 1969–1980.
- Cowgill GL (2004) Origins and development of urbanism: Archaeological perspectives. *Annual Review of Anthropology* 33: 525–549.
- d’Errico F and Stringer CB (2011) Evolution, revolution or saltation scenario for the emergence of modern cultures? *Philosophical Transactions of the Royal Society B: Biological Sciences* 366(1567): 1060–1069.
- Deville P et al. (2016) Scaling identity connects human mobility and social interactions. *Proceedings of the National Academy of Sciences* 113(26): 7047–7052.
- Ellis E, Maslin M, Boivin N et al. (2016) Involve social scientists in defining the Anthropocene. *Nature* 540: 192–193.
- Ellis EC (2015) Ecology in an anthropogenic biosphere. *Ecological Monographs* 85: 287–331.
- Ellis EC, Kaplan JO, Fuller DQ et al. (2013) Used planet: A global history. *Proceedings of the National Academy of Sciences* 110: 7978–7985.
- Emery NJ and Clayton NS (2004) The mentality of crows: Convergent evolution of intelligence in corvids and apes. *Science* 306(5703): 1903–1907.

- Erwin DH (2008) Macroevolution of ecosystem engineering, niche construction and diversity. *Trends in Ecology & Evolution* 23: 304–310.
- Feinman GM and Garraty CP (2010) Preindustrial markets and marketing: Archaeological perspectives. *Annual Review of Anthropology* 39: 167–191.
- Ferraro JV, Plummer TW, Pobiner BL et al. (2013) Earliest archaeological evidence of persistent hominin carnivory. *PloS one* 8(4): e62174.
- Fuller DQ (2010) An emerging paradigm shift in the origins of agriculture. *General Anthropology* 17: 1–12.
- Gamble C (1998) Palaeolithic society and the release from proximity: A network approach to intimate relations. *World Archaeology* 29(3): 426–449.
- Gamble C, Gowlett J and Dunbar R (2011) The social brain and the shape of the Palaeolithic. *Cambridge Archaeological Journal* 21(01): 115–136.
- Gillings MR, Hilbert M and Kemp DJ (2016) Information in the biosphere: Biological and digital worlds. *Trends in Ecology & Evolution* 31: 180–189.
- Goebel T, Waters MR and O'Rourke DH (2008) The late Pleistocene dispersal of modern humans in the Americas. *Science* 319(5869): 1497–1502.
- Grimm NB, Faeth SH, Golubiewski NE et al. (2008) Global change and the ecology of cities. *Science* 319: 756–760.
- Gutiérrez-Zugasti I, Cuenca-Solana D, del Río PR et al. (2013) The role of shellfish in hunter–gatherer societies during the Early Upper Palaeolithic: A view from El Cuco rockshelter, northern Spain. *Journal of Anthropological Archaeology* 32(2): 242–256.
- Haff P (2014) Humans and technology in the Anthropocene: Six rules. *The Anthropocene Review* 1: 126–136.
- Hamilton MJ, Burger O, DeLong JP et al. (2009) Population stability, cooperation, and the invasibility of the human species. *Proceedings of the National Academy of Sciences* 106: 12,255–12,260.
- Harari YN (2014) *Sapiens: A Brief History of Mankind*. London: Harvill Secker.
- Harmand S, Lewis JE, Feibel CS et al. (2015) 3.3-million-year-old stone tools from Lomekwi 3, West Turkana, Kenya. *Nature* 521(7552): 310–315.
- Head L (2014) Contingencies of the Anthropocene: Lessons from the 'Neolithic'. *The Anthropocene Review* 1: 113–125.
- Henrich J (2015) *The Secret of Our Success: How Culture Is Driving Human Evolution, Domesticating Our Species, and Making Us Smarter*. Princeton, New Jersey, USA: Princeton University Press.
- Henry AD and Vollan B (2014) Networks and the challenge of sustainable development. *Annual Review of Environment and Resources* 39: 583–610.
- Henry DO, Hall SA, Hietala HJ et al. (1996) Middle Paleolithic behavioral organization: 1993 excavation of Tor Faraj, southern Jordan. *Journal of Field Archaeology* 23(1): 31–53.
- Hill K, Barton M and Hurtado AM (2009) The emergence of human uniqueness: Characters underlying behavioral modernity. *Evolutionary Anthropology: Issues, News, and Reviews* 18: 187–200.
- Iakovleva L (2014) The architecture of mammoth bone circular dwellings of the Upper Palaeolithic settlements in Central and Eastern Europe and their socio-symbolic meanings. *Quaternary International* 359: 323–334.
- Isaac G (1978) The food-sharing behavior of protohuman hominids. *Scientific American*. 238(4): 90–109.
- Isbell F and Loreau M (2014) Sustainability of human ecological niche construction. *Ecology and Society* 19: 45.
- Jones CG, Lawton JH and Shachak M (1994) Organisms as ecosystem engineers. *Oikos* 69: 373–386.
- Kaplan HS, Hooper PL and Gurven M (2009) The evolutionary and ecological roots of human social organization. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364: 3289–3299.
- Kirch PV (2005) Archaeology and global change: The Holocene record. *Annual Review of Environment and Resources* 30: 409.
- Klein Goldewijk K, Beusen A and Janssen P (2010) Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene* 20: 565–573.

- Lackner KS and Wendt CH (1995) Exponential growth of large self-replicating machine systems. *Mathematical Computer Modelling* 21(10): 55–81.
- Laland KN and Brown G (2011) *Sense and Nonsense: Evolutionary Perspectives on Human Behaviour*. Oxford: Oxford University Press.
- Lambin EF, Turner BL, Geist HJ et al. (2001) The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change – Human And Policy Dimensions* 11: 261–269.
- Langejans GH, van Niekerk KL, Dusseldorp GL et al. (2012) Middle Stone Age shellfish exploitation: Potential indications for mass collecting and resource intensification at Blombos Cave and Klasies River, South Africa. *Quaternary International* 270: 80–94.
- Leakey LN, Leakey MG, Spoor F et al. (2012) New fossils from Koobi Fora in northern Kenya confirm taxonomic diversity in early Homo. *Nature* 488(7410): 201–204.
- Levin NE, Quade J, Simpson SW et al. (2004) Isotopic evidence for Plio–Pleistocene environmental change at Gona, Ethiopia. *Earth and Planetary Science Letters* 219(1): 93–110.
- Lewis SL and Maslin MA (2015) Defining the Anthropocene. *Nature* 519: 171–180.
- Lycett SJ, Collard M and McGrew WC (2009) Cladistic analyses of behavioural variation in wild Pan troglodytes: Exploring the chimpanzee culture hypothesis. *Journal of Human Evolution* 57(4): 337–349.
- Lyons TW, Reinhard CT and Planavsky NJ (2014) The rise of oxygen in Earth's early ocean and atmosphere. *Nature* 506: 307–315.
- McGrew WC (2004) *The Cultured Chimpanzee: Reflections on Cultural Primatology*. Cambridge: Cambridge University Press.
- McNabb J (1989) Sticks and stones: A possible experimental solution to the question of how the Clacton spear point was made. *Proceedings of the Prehistoric Society* 55(19,895): 251–271.
- McPherron SP, Alemseged Z, Marean CW et al. (2010) Evidence for stone-tool-assisted consumption of animal tissues before 3.39 million years ago at Dikika, Ethiopia. *Nature* 466(7308): 857–860.
- Malm A and Hornborg A (2014) The geology of mankind? A critique of the Anthropocene narrative. *The Anthropocene Review* 1: 62–69.
- Marzke MW (1997) Precision grips, hand morphology, and tools. *American Journal of Physical Anthropology* 102(1): 91–110.
- Matsuzawa T (2001) *Primate Foundations of Human Intelligence: A View of Tool Use in Nonhuman Primates and Fossil Hominids*. Springer Japan, pp. 3–25.
- Matthews B, De Meester L, Jones CG et al. (2014) Under niche construction: An operational bridge between ecology, evolution, and ecosystem science. *Ecological Monographs* 84: 245–263.
- Mesoudi A, Whiten A and Laland KN (2006) Towards a unified science of cultural evolution. *Behavioral and Brain Sciences* 29: 329–347.
- Nolan P and Lenski GE (2010) *Human Societies: An Introduction to Macrosociology*. 11th edition. Boulder, Colorado, USA: Paradigm Publishers.
- Nowell A (2010) Defining behavioral modernity in the context of Neandertal and anatomically modern human populations. *Annual Review of Anthropology* 39: 437–452.
- Odling-Smee FJ, Laland KN and Feldman MW (2003) *Niche Construction: The Neglected Process in Evolution*. Princeton, New Jersey, USA: Princeton University Press.
- Ortman S, Cabaniss A, Sturm J et al. (2014) *Settlement Scaling and Increasing Returns in an Ancient Society*. Science Advances 1:e1400066.
- Parfitt SA, Ashton NM, Lewis SG et al. (2010) Early Pleistocene human occupation at the edge of the boreal zone in northwest Europe. *Nature* 466(7303): 229–233.
- Pettitt PB (1997) High resolution Neanderthals? Interpreting middle palaeolithic intrasite spatial data. *World Archaeology* 29(2): 208–224.
- Richerson PJ and Boyd R (2005) *Not By Genes Alone: How Culture Transformed Human Evolution*. Chicago, Illinois, USA: University of Chicago Press.
- Pope MI (2002) *The significance of biface-rich assemblages: An examination of behavioural controls on lithic assemblage formation in the Lower Palaeolithic*. Doctoral dissertation, University of Southampton.

- Pope MI and Roberts MB (2005) *Observations on the Relationship Between Palaeolithic Individuals and Artefact Scatters at the Middle Pleistocene Site of Boxgrove, UK*. London: Routledge.
- Potts R (1988) *Early Hominid Activities at Olduvai*. London: Routledge.
- Roberts MB and Parfitt SA (1999) *Boxgrove: A Middle Pleistocene Hominid Site at Earham Quarry, Boxgrove, West Sussex*. London: English Heritage.
- Roebroeks W and Villa P (2011) On the earliest evidence for habitual use of fire in Europe. *Proceedings of the National Academy of Sciences* 108(13): 5209–5214.
- Schick K (1992) Geoarchaeological analysis of an Acheulean site at Kalambo Falls, Zambia. *Geoarchaeology* 7(1): 1–26.
- Schmidt JJ (2017) Social learning in the Anthropocene: Novel challenges, shadow networks, and ethical practices. *Journal of Environmental Management* 193: 373–380.
- Semaw S, Rogers MJ, Quade J et al. (2003) 2.6million-year-old stone tools and associated bones from OGS-6 and OGS-7, Gona, Afar, Ethiopia. *Journal of Human Evolution* 45(2): 169–177.
- Seto KC, Reenberg A, Boone CG et al. (2012) Urban land teleconnections and sustainability. *Proceedings of the National Academy of Sciences* 109: 7687–7692.
- Smith BD (2012) A cultural niche construction theory of initial domestication. *Biological Theory* 6: 260–271.
- Smith BD and Zeder MA (2013) The onset of the Anthropocene. *Anthropocene* 4: 8–13.
- Smith ME (2004) The archaeology of ancient state economies. *Annual Review of Anthropology* 33: 73–102.
- Smith ML (2014) The archaeology of urban landscapes. *Annual Review of Anthropology* 43: 307–323.
- Sterelny K (2011) From hominins to humans: How sapiens became behaviourally modern. *Philosophical Transactions of the Royal Society B: Biological Sciences* 366: 809–822.
- Sterelny K (2014) A Paleolithic reciprocation crisis: Symbols, signals, and norms. *Biological Theory* 9: 65–77.
- Trinkaus E, Buzhilova AP, Mednikova MB et al. (2014) *The People of Sunghir: Burials, Bodies, and Behavior in the Earlier Upper Paleolithic*. Oxford: Oxford University Press.
- Ungar PS (2012) Dental evidence for the reconstruction of diet in African early Homo. *Current Anthropology* 53(S6): S318–S329.
- Waring TM, Kline MA, Brooks JS et al. (2015) A multilevel evolutionary framework for sustainability analysis. *Ecology and Society* 20: 34.
- Waters CN, Zalasiewicz J, Summerhayes C et al. (2016) The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science* 351: 262–273.
- White MJ (2006) Things to do in Doggerland when you're dead: Surviving OIS3 at the northwestern-most fringe of Middle Palaeolithic Europe. *World Archaeology* 38(4): 547–575.
- Zalasiewicz J, Crutzen PJ and Steffen W (2012) The anthropocene. In: Gradstein FM, Ogg JG, Schmitz M et al. (eds) *The Geologic Time Scale 2012*. Amsterdam: Elsevier Science, 2 vols., pp. 1033–1040.
- Zalasiewicz J, Williams M, Waters CN et al. (2014) The technofossil record of humans. *The Anthropocene Review* 1: 34–43.
- Zeder MA (2016) Domestication as a model system for niche construction theory. *Evolutionary Ecology* 30: 325–348.