Technology as a geological phenomenon: implications for human well-being

P. K. HAFF

Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Box 90233, Durham, North Carolina 27516, USA (e-mail: haff@duke.edu)

Abstract: The technosphere, the interlinked set of communication, transportation, bureaucratic and other systems that act to metabolize fossil fuels and other energy resources, is considered to be an emerging global paradigm, with similarities to the lithosphere, atmosphere, hydrosphere and biosphere. The technosphere is of global extent, exhibits large-scale appropriation of mass and energy resources, shows a tendency to co-opt for its own use information produced by the environment, and is autonomous. Unlike the older paradigms, the technosphere has not yet evolved the ability to recycle its own waste stream. Unless or until it does so, its status as a paradigm remains provisional. Humans are ‘parts’ of the technosphere – subcomponents essential for system function. Viewed from the inside by its human parts, the technosphere is perceived as a derived and controlled construct. Viewed from outside as a geological phenomenon, the technosphere appears as a quasi-autonomous system whose dynamics constrains the behaviour of its human parts. A geological perspective on technology suggests why strategies to limit environmental damage that consider only the needs of people are likely to fail without parallel consideration of the requirements of technology, especially its need for an abundant supply of energy.

The case for a new geological epoch has been articulated by Crutzen and others (e.g. Crutzen & Stoermer 2000; Crutzen 2002; Steffen *et al.* 2011) with the argument that the impact on and co-option of natural processes by human actions has become sufficiently intense that the characteristics of the recent but mostly natural Holocene world no longer adequately correspond to the suite of Earth surface processes operating today. Among the consequences of human actions that have or are threatening to significantly alter natural Earth function are the exploitation of a large fraction of the Earth’s land surface for human purposes, 38% of which was agricultural land in 2009 (FAO 2011), fixation of more atmospheric nitrogen than fixed by all natural terrestrial processes (Vitousek *et al.* 1997), appropriation of terrestrial organic material equivalent to 40% of net primary production (Vitousek *et al.* 1986), extinction of biological species, which, at the current rate, exceeds that leading up to the ‘Big Five’ mass extinction events of geological history (occurring at the end of the Ordovician, Devonian, Permian, Triassic and Cretaceous periods) (Barnosky *et al.* 2011), interception by dams of 25–30% of global sediment load (Vorosmarty *et al.* 2003), impoundment of up to 15% of global runoff (Nilsson *et al.* 2005) and consumption of energy at *c.*20% of the rate of photosynthetic energy flow through the biosphere (Sassoon *et al.* 2009). Moreover there is an expectation of continued change in Earth function as a consequence of human activity (IPCC 2007), including further warming of the atmosphere, shifts in the geographical distribution of species, continued recession of glaciers, melting of permafrost, vanishing of late-summer Arctic sea ice, and continued sea-level rise. To emphasize the importance of human actions on Earth function, a new name, ‘Anthropocene’, has been proposed for the modern geological epoch (Crutzen & Stoermer 2000).

Technology from the outside

The logic of inaugurating a new nomenclature to reflect the changed and changing conditions of the globe over the past few centuries is convincing. Here, we offer a slightly different emphasis on the nature of this recent transition out of the Holocene by highlighting the role that technology plays in defining the world we now inhabit. The proliferation of technology across the globe defines the technosphere – the set of large-scale networked technologies that underlie and make possible rapid extraction from the Earth of large quantities of free energy and subsequent power generation, long-distance, nearly instantaneous communication, rapid long-distance energy and mass transport, the existence and operation of modern governmental and other bureaucracies, high-intensity industrial and manufacturing operations including regional, continental and global distribution of food and other goods, and a myriad additional ‘artificial’ or ‘non-natural’ processes without which modern

From: Waters, C. N., Zalasiewicz, J. A., Williams, M., Ellis, M. A. & Snelling, A. M. (eds) *A Stratigraphical Basis for the Anthropocene*. Geological Society, London, Special Publications, **395**,
http://dx.doi.org/10.1144/SP395.4

civilization and its present 7×10^9 human constituents could not exist. If the term 'anthroposphere' is meant to emphasize the role of human beings as causative agents responsible for Earth transformations that define the Anthropocene, the use of 'technosphere' suggests a more detached view of an emerging geological process that has entrained humans as essential components that support its dynamics. (To aid readability, and where confusion will not result, the word 'technology' is sometimes used below as a synonym for 'technosphere'.)

Because we design, manufacture, deploy and maintain many of the parts, or 'artefacts', of which technology is composed, and then network them together to obtain a desired function, it is natural for humans to see the technosphere from the 'inside' and to think of it as a purely derivative phenomenon, dependent entirely on humans for its creation and continued existence. However, that is only half the story. The human population, at anything like its current size, is deeply dependent on the existence of the technosphere. Without the support structure and services provided by technology, the human population would quickly decline towards its Stone Age base of no more than ten million (US Census Bureau 2012) individuals. The technosphere is not 'just' a human-created phenomenon, because, except for simple artefacts like stone tools, humans did not create technology independently, but only in the context of existing technological systems. From the outside, that is, from its own vantage point, notwithstanding that its human parts are essential, technology appears to have bootstrapped itself into its present state. This is the same process that characterizes all emergent complex systems vis-à-vis their small-scale components; that is, large-scale dynamics appears spontaneously (e.g. Laughlin & Pines 2000; Werner 2003) and defines an environment within which small system components must operate.

Moreover, small components (which may themselves be systems) that are essential to overall system function often do not operate independently, but are constrained by and often depend for their existence on the emergent properties for which their own actions provide necessary support. If the parts are simple enough, they can survive the demise of the emergent system they once helped define, as sand grains remain when the dune disperses. However, more complex parts, like the stratigraphic layers inside a dune, often can maintain their existence only in the environment they help create (signature aeolian stratigraphy vanishes with the dune). Similarly, in the ruins of collapsed civilizations, surviving parts tend to be simple and inert, like the scattered stone blocks that once cooperated to define a building or monument. The more complex, dynamic parts of the civilization – buildings, institutions and cities – often cannot maintain their existence if the larger system they helped define ceases to exist. In a similar way, humans have become entrained within the matrix of technology and are now borne along by a supervening dynamics from which they cannot simultaneously escape and survive.

In this paper we adopt the non-anthropocentric view that technology is a global phenomenon that follows its own dynamics, representing something truly new in the world – the opening phase of a new paradigm of Earth history. In this sense one might say that technology is the next biology.

Commonalities and contrasts between technology and earlier paradigms

Global extent

Identifying commonalities between the technosphere and older geological paradigms helps paint a clearer picture of the potential role of the technosphere as a defining and potentially enduring mode of Earth organization. Identifying contrasts on the other hand helps to show how the technosphere must evolve if it is to finally attain a true paradigmatic status.

Geological paradigms are recognized as such partly because their dynamics are far-reaching – indeed global – in extent, like the paradigms expressed by the hydrological cycle, atmospheric circulation, plate tectonics and biological processes. In recognition of the fact of global coverage we refer to the spheres: the hydrosphere, the atmosphere, the lithosphere and the biosphere. In a similar way technology penetrates to nearly every part of the globe through a web of communication and transportation networks. On land the technosphere transports large quantities of solids further and faster than any natural process except sediment transport by rivers (Haff 2010). The technosphere is also manifest in the wide distribution of myriad artefacts such as needles, motors and medicines, and by technological or technologically assisted processes like pumping and harvesting, as well as by nominally human activities that are closely tied to technological processes, such as watching television or filling out tax forms. Most such localized systems, processes and artefacts derive from, or are connected either directly or indirectly to, the globe-spanning networks of the technosphere.

If we take the State (capitalized to indicate a political entity rather than a generic state of a system) as an example of a large coherent component of the technosphere, then almost all the world's people are parts of (subject to) States and thus are parts of the modern technosphere. The principal exceptions are certain populations that occupy mountainous or other difficult-to-access terrains, such as swamplands. One of the best studied (Scott 2010) examples of these remote, outside-the-modern-technosphere populations is Zomia (population on the order of 100 million), a rugged, mountainous region in SE Asia that is congruent with no State but laps across the boundaries of China, Vietnam, Thailand and other internationally recognized polities. Here, the early technosphere appeared in the last millennium or two in the form of States occupying valley bottoms and depending for their existence on wet-rice cultivation and the presence of large, sedentary human populations. The mountainous hinterlands of Zomia provided protection over many centuries for tribal peoples who, surviving through swidden agriculture and non-sedentary ('nomadic') lifestyles, rejected the hegemony of the valley States, which were unable to easily project power beyond the smooth flatlands that sustained the valley padis. Continued evolution of technology with instantaneous communications over great distances, domination of the third dimension by aircraft, and introduction of heavy machinery to construct roads and railways through difficult terrain had, by the mid-twentieth century, threatened the existence of humanity's largest, and one of its last, refugia from the technosphere. In subduing the last vestiges of mass resistance to assimilation, the technosphere seems to be approaching, as if towards a mathematical limit, domination of 100% of the world's people. The technosphere is in any practical sense a global phenomenon, spanning the planet and absorbing into itself almost all of the world's human population.

Appropriation of resources

The physical components of a geological paradigm are constructed from parts cadged from the Earth's supply of resources, including from resources used by older paradigms. For example, the biosphere is built up in large part of carbon, oxygen and hydrogen (water) abstracted from the atmosphere and the hydrosphere, and incorporates inorganic atoms derived from mineral grains in the lithosphere. The technosphere abstracts water from the hydrosphere for urban consumption, irrigation and to supply industry, appropriates organic material from the biosphere (such as wood and agricultural products), uses material from the lithosphere for building materials and foundations and as a medium to support agriculture, and captures oxygen from the atmosphere to support the combustion of its main energy source, fossil fuels derived ultimately from the biosphere, as well as for the burning of food calories, which power its human and other animal parts.

Redesigned organisms, such as those that comprise livestock and cereal grains or that produce fibres for textiles, can be interpreted as newly constructed parts of the technosphere rather than as appropriated parts of the biosphere. Although the processes that govern domesticated organismal metabolism are essentially the same as those of related organisms in the natural biosphere, the domesticated organisms themselves exist with their present large populations only because of technological processes that support them and which they in turn support. Most of the physical organisms themselves were never part of the natural biosphere but were born, so to speak, directly into the technosphere. Only the information on how to construct them was appropriated. In the same way, human organisms, whose function is essential to the existence of the technosphere, can be viewed as newly constructed technological parts based on old design information (DNA) captured from the biosphere.

Besides appropriating mass and information, a geological paradigm must capture for its own use some fraction of existing energy stores and flows. Because geological paradigms are dynamical systems that help to define the global environment, their power requirements are large (data in the following from Sassoon *et al.* 2009; see also Hermann 2006). Units of power are terawatts, TW (10^{12} W). From an incident solar flux of *c.* 162 000 TW, the atmosphere absorbs energy (or destroys or converts exergy, or usable energy) at a rate of 31 000 TW, of which *c.* 870 TW appears as kinetic energy of the winds. The hydrosphere absorbs another 41 000 TW in evaporating water. Absorption by the biosphere of 15 000 TW leads via photosynthesis to the generation of chemical energy in plant matter at a rate of *c.* 90 TW, of which the technosphere appropriates almost 10 TW (agriculture and forestry). Fossil fuels, uranium and renewable energy sources provide energy to the technosphere at a rate of *c.* 17 TW (IEA 2012). This is an appreciable fraction of the geothermal energy flux (32 TW), the biochemical energy flux (90 TW) and the gravitational power load of the world's rivers (7 TW), suggesting the susceptibility of parts of the land surface, the biosphere and the fluvial portion of the hydrosphere to disruption or appropriation by the technosphere.

Geological paradigms emerge when a large energy source is available and the environment contains many similar parts whose individual properties provide a basis for collective use of available energy to perform work. Molecules of oxygen, nitrogen and water are abundant; they form fluids under a wide range of environmental conditions

(conditions of temperature and pressure that their own collective properties help create), and, under forcing powered ultimately by solar radiation, they constitute large aggregated volumes of water and air that flow across the planet. Because each molecule of a given type has identical properties, essentially all molecules that can potentially participate in their respective cycles actually will participate if the energy supply is large enough. In a similar way, for humans, the distribution over a large number of individuals of characteristics such as acquisitiveness that result in demand for goods and services requiring energy to manufacture and deliver, renders human parts susceptible to entrainment into large-scale collective behaviour in the presence of a suitably large accessible energy source, such as fossil fuels. As with the molecules that support the atmospheric and hydrological paradigms, similarities between parts make it probable that each human participates in the dynamics of the emerging technological paradigm.

If the inclination to acquire is not saturated at a given level of average per capita energy consumption, there is scope for technological energy consumption to increase. The 'principle of maximum entropy production' (PMEP) asserts that sufficiently complex dynamic systems will evolve to a state in which usable energy is consumed as fast as possible, consistent with extant constraints (Kleidon & Lorenz 2005). Although not proven (but see Niven 2009), PMEP appears to have had some success in application to energy consumption by the Earth's atmosphere in predicting the distribution of average meridional temperature and cloudiness (Paltridge 1975). PMEP applies to steady-state systems and thus is not expected to describe the present state of rapidly accelerating technological energy use. However, if a state of higher energy consumption can potentially be realized, that is, if there are no constraints that prohibit a faster rate of energy consumption, then PMEP suggests that the technosphere will tend to evolve towards increased appropriation of usable energy (Haff 2013), bearing its human parts along in the process.

Conservative nature of geological paradigms

Geological paradigms are conservative. The elements and functionality of pre-existing paradigms can survive the emergence of a new geological paradigm, even in the face of capture of some of their structural and metabolic resources. In a thermodynamic transition occurring less than 200 hundred million years after the formation of the molten planet, the Earth's surface solidified (Wilde *et al.* 2001), representing an early crustal paradigm; the pre-existing magma ocean did not disappear, however, but lived on just beneath. Later in Earth history, the biosphere arose and modified the atmosphere (e.g. by oxygenation), the hydrosphere (by influencing precipitation patterns, groundwater levels and river flow) and the solid Earth surface (by enhancing weathering and soil formation and by impeding erosion), but the earlier paradigms continued to function, if in modified ways. The winds still blew, the rivers still flowed, and mountain ranges still rose and fell. More recently, technology has appropriated large quantities of 'natural resources' from the biosphere, hydrosphere and lithosphere, but, at least for the time being, the ancient paradigms continue as globally organized systems. One reason for the conservatism of paradigms is that the conditions required for their emergence and function were defined to a large extent by the pre-existing environment, which provided a framework conducive to the gestation of the new paradigm and without which ramp-up of the emergent dynamics would not be possible. For example, plate tectonics required the continued existence of the fluid Earth – if in modified form – in order for plates to move across the Earth's surface, to subduct and for new plates to form, while biological systems required the continuing function of the hydrological cycle, and so on.

Technology emerged on an Earth filled with materials, energy stores and flows, and functioning dynamical systems that were products or components of these earlier natural paradigms. Processes, systems and stores that today remain essential to human well-being (and thus to technological function) comprise the elements of what is called natural capital (e.g. Daily 1997). Natural capital includes the Earth's thick, fertile soils, mineral resources, bacterial and chemical populations that breakdown or recycle wastes, sources of fresh water, soil mechanisms that filter or detoxify contaminants, a reasonably stable and equable climate, and biological diversity, among many other examples. A principal criticism of the rapidly expanding growth of technology centres on its non-conservative function, that is, on the effects of the destruction of natural capital as measured by (high) rates of, for example, urban growth, land-use change, destruction of rain forests, extinction of biological populations, and consumption of finite stores of oil, gas, coal and other Earth materials on which our well-being depends. Their conservative nature still serves earlier paradigms, but technology seems to be on a course to abandon the conservative dynamics that has been essential for its emergence and function. Technology is the first geological paradigm complex enough to become aware, through its human components, of the essential contribution to its own existence of the support provided by established paradigms. Whether this awareness will lead to the conservation of a sufficient quantity of natural capital to maintain technological function (and thus the well-being of humans) is the basic question of environmental science. The answer to this question may also determine whether or not the technosphere will, in the long run, become an established rather than a failed geological paradigm.

Recycling of mass resources

Recycling of mass resources plays an essential role in the function of established geological paradigms. A water drop falling from a cloud on its way to the ocean must be replaced by an equivalent mass of evaporated (recycled) water or the hydrosphere will soon cease operation for lack of atmospheric moisture. Whether it be the lithosphere, hydrosphere, atmosphere, biosphere or technosphere, over a long enough period of time the (finite) mass resources on which paradigm function depends will be drawn down in the absence of recycling, leading to limitations on paradigmatic activity. In biology, Liebig's law of the minimum (Odum 1971) stipulates that plant population growth is controlled by the availability of the 'scarcest' nutrient. Return of nutrients to the soil by organisms is a recycling process that helps limit the effects of scarcity of essential minerals. The technosphere recycles some kinds of materials. Over much of the history of technology, metals like gold and silver have served an important role in facilitating mass and energy flows through society. Coinage was not discarded after a sale, but instead soon returned to the monetary circulatory system. Many other metals are important nutrients for technological metabolism (e.g. rare earth metals), and a few are used as major structural elements (principally iron and aluminium). As ore deposits are exhausted, metal recycling (e.g. Rauch & Pacyna 2009; Goldstein 2012) will become increasingly necessary if the technosphere is to maintain its high level of metabolic function. However, at the present time, the technosphere is a poor recycler of many of the critical resources that it uses.

In a closed environment like the Earth (essentially no mass input or output), every metabolizing system must eventually recycle its own waste products (or rely on other systems to do so), otherwise accumulation of spent material (i.e. pollutants) will impair system function. If leaf litter produced by a forest were not recycled it would soon build up to a point where the trees that produced it were buried by their own detritus. In the case of the technosphere, the most important example of mass pollution may be the buildup of atmospheric carbon dioxide. Warming of the atmosphere is likely to lead to rapid sea-level rise and submergence of coastal cities and infrastructure, putting as many as 200 million people at risk of becoming environmental refugees (Myers 2002). The ensuing climate disruption could also lead to large-scale crop failures through drought, flood, pest infestations or other possible impacts of climate destabilization (Ehrlich & Ehrlich 2013). Failure of even a modest fraction of the industrial global agriculture enterprise (which in its use of nitrogen fixed through the Haber–Bosch process is estimated to support *c.* 40% of the world's population; Smil 1999) would be a disaster for humanity. If continued carbon emission without recycling should ultimately degrade or eliminate the participation of a large enough number of humans in their active roles as technospheric parts, then the metabolism of the technosphere would decline.

The recycling shortcomings of the technosphere with respect to carbon and other essential inputs may make it appear a poor candidate for a new paradigm, especially when compared to the ability of, say, the biosphere to recycle its own waste. However, this comparison is somewhat misleading. Over geological history the biosphere has also failed to recycle its own wastes, with catastrophic consequences for many species. In the time leading up to the Great Oxidation Event about 2.4 billion years ago (e.g. Lenton & Watson 2011), proto-cyanobacteria evolved that were capable of oxygenic photosynthesis, using sunlight to split water, freeing up electrons for metabolic use. These novel organisms, however, failed to recycle the resulting toxic oxygen waste stream. As a consequence of loading the atmosphere with large quantities of poisonous waste, much of the rest of the biosphere was forced to evolve mechanisms to detoxify or respire oxygen, or to retreat to sequestered anaerobic environments (Sessions *et al.* 2009).

Today, the biosphere is, in the main, an effective recycler of its own wastes, partly as a consequence of the long period of time that evolution has had to select against organisms that degrade their own ability to reproduce by polluting their environment or that are unable to tolerate levels of environmental pollution generated by the rest of the biosphere. That technology exhibits a massive failure to recycle may be a consequence of its status as a new geological phenomenon. Over a long enough period of time, mass flow loops may close. Whether the rapid pace of technological change will generate effective recycling mechanisms for the resulting waste stream soon enough to limit having a large impact on the climate, and hence a braking effect on technology, is unknown. Although technology-driven climate change may exacerbate key vulnerabilities in areas such as food supply, infrastructure and human health (Schneider *et al.* 2007), to the detriment of human as well as technospheric well-being, the ability to recycle at a rate that can maintain current environmental conditions is not necessarily a requirement for the continued emergence of a technological paradigm. The experience of the biosphere in the wake of the Great Oxidation Event shows that even a massive failure to recycle environmental pollutants need not necessarily signal the end of a paradigm. If technological recycling fails to spin up soon enough to avoid catastrophic (as seen by humans) reorganization of global Earth function, that may not be the end of the game but just a change in rules. In the extreme case that *Homo sapiens* became extinct, then presumably the emergence of the technological paradigm would stop, and the evidence of the brief technological excursion by the Earth would be compressed to a thin line in the future sedimentary record. Technology would have been an event, analogous to the Cretaceous–Tertiary impact, not a new paradigm of Earth function. However, if human extinction does not occur, then the technosphere may survive the large changes in environmental variables that it is causing, as has been the case for the biosphere. By adjusting to the new Earth environment, in company with a stressed but surviving human population, the technosphere may evolve in ways we cannot predict or perhaps even imagine.

Autonomy of paradigms

Natural geological paradigms that emerged before humans came on the scene were autonomous. That is, by definition they needed no human deliberation or control in order to function, a condition that might seem to distinguish them from the technological paradigm. We tend to see technology as a human construct under our control. Technology seems to us not autonomous but critically dependent on humans and human actions. Humans design, manufacture, construct, deploy and maintain key elements of the technosphere. Certainly, the technosphere could not exist without its human component. On the other hand, neither can any other system maintain its existence without the participation of its components – the hydrological cycle could not exist without the supporting activity of its water molecules, the rock cycle without its mineral components, and so on. That the technosphere requires for its function the participation of certain critical parts, even if they are people, does not by itself distinguish it from other geological paradigms.

One apparent difference between the technosphere and other paradigms is that for classical geological paradigms like the hydrosphere, the parts seem to come along for the ride: a drop or molecule of water is borne along in the hydrological cycle like an object on a conveyor belt. Technological systems on the other hand are often seen as driven by human decision and human actions (Haff 2012). People are proactive; technology is reactive. The computer responds to human intentions and commands. Not only did people design and manufacture it, but we personally decide how to use it – when to plug it in, turn it on, what keys to hit, and so on. The autonomous nature of technology comes more clearly into view when we move beyond technological artefacts that people interact with directly and consider larger technological systems, which contain people among their parts.

A refrigerator is a technological artefact over which the owner has some control, but the electric power grid to which the refrigerator is connected is not under the owner's control. In fact, the power grid is not really under anyone's control. It is quasi-autonomous in the sense that it cannot be shut down by human decision except for short periods of time, and most of its function occurs without human intervention or even knowledge. However, because modern complex society could not function without an essentially continuous supply of electricity, the grid must be functional most of the time for the present technosphere to exist, independent of the actions of any person or group of persons. Any large-scale attempt to shut down the flow of electricity would meet immediate resistance. Periods of disruption or failure in a tightly coupled system, like a regional component of a national power grid, are possible in the event of sabotage or the chance occurrence of rare but small cascading events, but such failures are more in the nature of glitches from which recovery is eventually possible rather than examples of terminal failure. The makeup of the grid with its rugged components, backup systems, redundancy, reserve capacity, alarms and other security systems make it much more than just a system that satisfies the basic physical requirements for generating and distributing electric power. If this is all it were, then the grid would have the same characteristics as a table-top physics experiment that could be arbitrarily taken down or reconfigured on the fly by human decision. Instead, the grid bristles with protective capabilities that help avoid or defend against challenges, human or otherwise, to its basic function. It is as if the table-top laboratory apparatus were to get a mind of its own and strongly resist any actions by the experimenter that threatened its functionality. In other words, the power grid is autonomous.

Moreover, the property of autonomy is sufficiently well developed that it trickles down even to the technological artefacts that we normally think we control. We open and close the refrigerator on impulse, but it is very difficult for a typical 'owner' to unplug his refrigerator for any extended period of time – say for a few days. This is an objective observation that the reader can test for himself. The refrigerator shares a part of the autonomy of the grid to which it is connected and resists challenges to its functionality, especially attempts to cut off its power source.

The technosphere thus exhibits a number of properties of earlier geological paradigms. It is autonomous. It is a global phenomenon. It appropriates Earth resources, including energy, mass and information, for its own uses on a large scale. However, unlike earlier Earth paradigms, which recycle most of their waste products, the technosphere does little recycling. The future of the technosphere as a paradigm rather than just an episode in Earth history is contingent upon the emergence of effective recycling mechanisms.

Implications of the new paradigm

There is strategic value in looking at technology from the 'outside' as an emerging geological phenomenon. The problem of coping with the consequences of technology and technological change offers different answers, depending on whether we think of technology primarily as a human-generated and controlled phenomenon, or whether we look at it as a quasi-autonomous phenomenon that in effect operates according to its own dynamics. Looking at technology from the inside, we tend to formulate solutions to the problem of natural capital degradation that draw a straight line from the seemingly excessive use of resources like energy to policies that might restrict such use. However, prescriptions such as constricting the resource stream on which the function of technology depends, for example by taxing carbon, tend to encounter resistance. Technology is not passive but has evolved mechanisms for its own defence – a requirement of any dynamic system whose longevity is measured in a large number of internal clock cycles, such as the time between cell phone bills or elections. The most important of these defenses is preemptive in nature and takes advantage of fundamental properties of its human parts, especially the property of acquisitiveness. Technology defends its mode of operation primarily by offering incentives such as abundant food, medicines, instant communication channels and other desiderata that bind, or even addict, humans to the system that produces them, as well as by less subtle mechanisms expressed via legal, judicial, political, military and other elements of the technological armory. The upshot is that attempts to ratchet back the rate of energy use and of consumption of the other resources on which this cornucopia depends, or to interfere with the continuing diversification and penetration of technology as it seeks out new sources of energy and material resources, are automatically resisted by the feedback loops on which technological metabolism is based. This is the nature of a positive feedback loop – it has intrinsic stability against disruption – the twist here being that humans, as sentient components of such a loop, may feel surprise or dismay upon realizing their enforced participation in a dynamics they thought they controlled. Policies that are based only on a consideration of future human well-being and do not take into account the needs of technology, especially the need to continue metabolizing at a high rate – which is the source of the constraints and incentives that channel human behaviour towards technology-friendly activities and is thus the *sine qua non* of technology – are likely to fail or be slow to implement because they consider the implicit two-way compact between system and parts only from the viewpoint of the parts.

With respect to human well-being, a high rate of technological energy consumption is, by itself, not the central problem. Global warming is not a necessary consequence of a high rate of energy use, but of the lack of adequate recycling mechanisms. The hydrosphere consumes energy more than a thousand times faster than the technosphere, but it recycles its own waste (fallen rainwater). The technosphere, in burning fossil fuels, operates without any provision to recycle a major waste product, carbon. From the point of view of an autonomous technosphere, climate change is not a problem to be solved by using less energy, but by using more energy. As seen from the dynamics of the Carnot engine, whatever useful work is done by a system, additional energy is required to power a recycling mechanism.

Efforts to ramp up 'renewable' energy sources such as those based on wind or photovoltaics offer new ways to use energy to do work without the principal drawback of fossil-fuel combustion, that is, without the need to recycle carbon. However, renewables technology is still technology. Trying to fix the climate problem by turning to renewables may therefore not lead where it seems. This will be the case if opportunities offered by renewables appear different to the technosphere than to humans. The emergence of new technological subsystems that can capture abundant but previously unavailable or little-used renewable resources like that provided by sunlight may just as likely be an opening move in the expansion of the technosphere towards massive increases in the use of these new resources than simply a way to substitute new cleaner energy sources for older sources that degrade the environment. For example, with regard to solar energy, there is no reason to expect that the technosphere will limit itself to extracting energy from just the fraction of the solar radiation flux that happens to be incident on the planetary disk. Technology is already extending itself into space and it may not be indifferent to the large fluxes of solar energy available there. Geoengineering proposals to counteract global warming by deploying a cloud of refractive 'flyers' in space to deflect incident solar energy away from the Earth are already on the books (Angel 2006). However, deflecting sunlight is throwing away usable energy. It is a short step to see how this idea might be retuned to do just the opposite – to capture the energy of photons in space that would have missed the Earth and then transmit the energy down to the Earth's surface (e.g. in the form of microwaves; Glaser 1968). This is not a prediction, but illustrates how looking at the technosphere from the outside provides its own perspective on possible Earth futures.

Whatever the future of particular renewable energy sources, the driving forces are already in place for transition to rates of energy consumption that are larger than, and perhaps much larger than, the current power level of fossil-fuel use. Two such drivers are the unsatisfied aspirations of the world's energy-poor humans and the need to recycle wastes. Average global per capita energy use (2010) is about 40% of the rate of per capita energy consumption in Organisation for Economic Co-operation and Development (OECD) countries (IEA 2012). Closing this gap would require an increase in the power level of the technosphere by a factor of about 2.5, from 17 TW to 42 TW. To bring world per capita energy use to the level of North American consumption would require an increase by a factor of 4 to a total of 68 TW. The need to recycle metabolic waste products generated by an increasingly energy-consumptive population would further increase power demand. With the appearance of effective technospheric recycling mechanisms, a third easily imagined driver of future energy consumption would be the realization that the current level of per capita energy use in rich societies does not represent any kind of natural or intrinsic or perhaps even desirable limit to the rate at which one might use energy. If the lives of people in rich societies today are supported by energy use at an average per capita rate of 10 kW (US in 2011; EIA 2012), the question may arise of why not 20 kW in the future, for everyone? Real-time decisions and choices by humans within the context of their cultural and political institutions will help determine the details of how potential drivers translate into future energy use. However, looking at the world from the point of view of a still emerging geological paradigm we should expect that the framework for our decisions and choices will be shaped and guided by the needs of the technosphere as well as by human needs.

I would like to thank N. Cassar and E. Goldstein for critical commentary and for suggestions for improving the manuscript.

References

Angel, R. 2006. Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1). *Proceedings of the National Academy of Science of the USA*, **103**, 17 184–17 189. http://dx.doi.org/10.1073/pnas.0608163103

Barnosky, A. D., Matzke, N. *et al.* 2011. Has the Earth's sixth mass extinction already arrived? *Nature*, **471**, 51–57. http://dx.doi.org/10.1038/nature09678

Crutzen, P. J. 2002. Geology of mankind. *Nature*, **415**, 23.

Crutzen, P. J. & Stoermer, E. F. 2000. The Anthropocene. *Global Change Newsletter*, **41**, 17–18.

Daily, G. C. (ed.) 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press, Covelo.

Ehrlich, P. R. & Ehrlich, A. H. 2013. Can a collapse of global civilization be avoided? *Proceedings of the Royal Society B*, **280**, 20122845. http://dx.doi.org/10.1098/rspb.2012.2845

EIA 2012. *Annual Energy Review 2011*. US Energy Information Agency, DOE/EIA-0384(2011). http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf

FAO 2011. *FAOSTAT*. Food and Agricultural Organization of the United Nations. http://faostat.fao.org/site/377/DesktopDefault.aspx?PageID=377#ancor

Glaser, P. E. 1968. Power from the Sun: its future. *Science*, **162**, 857–861.

Goldstein, E. 2012. *Possible dynamics of technological metals in the Anthropocene*. *2012 Fall Meeting of the American Geophysical Union.* Abstract GC53C-1292. http://fallmeeting.agu.org/2012/eposters/eposter/gc53c-1292/

Haff, P. K. 2010. Hillslopes, rivers, plows, and trucks: mass transport on Earth's surface by natural and technological processes. *Earth Surface Processes and Landforms*, **35**, 1157–1166. http://dx.doi.org/10.1002/esp.1902

Haff, P. K. 2012. Technology and human purpose: the problem of solids transport on the Earth's surface. *Earth System Dynamics*, **3**, 417–431. http://dx.doi.org/10.5194/esd-3-149-2012

Haff, P. K. 2013. Maximum entropy production by technology. Accepted for publication. *In*: Dewar, R. C., Lineweaver, C., Niven, R. & Regenauer-Lieb, K. (eds) *Beyond the Second Law: Entropy Production and Non-Equilibrium Systems*. Springer, Berlin, in press

Hermann, W. A. 2006. Quantifying global exergy resources. *Energy*, **31**, 1685–1702.

IEA 2012. *Key World Energy Statistics*. International Energy Agency. http://www.iea.org/publications/freepublications/publication/kwes.pdf

IPCC 2007. *IPCC Fourth Assessment Report: Climate Change 2007. Intergovernmental Panel on Climate Change*. http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#1

Kleidon, A. & Lorenz, R. (eds) 2005. *Non-Equilibrium Thermodynamics and the Production of Entropy: Life, Earth, and Beyond*. Springer, Berlin.

Laughlin, R. B. & Pines, D. 2000. The theory of everything. *Proceedings of the National Academy of*

Science of the USA, **97**, 28–31. http://dx.doi.org/10.1073/pnas.97.1.28

Lenton, T. & Watson, A. 2011. *Revolutions That Made the Earth*. Oxford University Press, New York.

Myers, N. 2002. Environmental refugees: a growing phenomenon of the 21st century. *Philosophical Transactions of the Royal Society London B*, **357**, 609–613. http://dx.doi.org/10.1098/rstb.2001.0953

Nilsson, C., Reidy, C. A., Dynesius, M. & Revenga, C. 2005. Fragmentation and flow regulation of the world's large river systems. *Science*, **308**, 405–408.

Niven, R. K. 2009. Steady state of a dissipative flow-controlled system and the maximum entropy production principle. *Physical Review E*, **80**, 021113. http://dx.doi.org/10.1103/PhysRevE.80.021113

Odum, E. P. 1971. *Fundamentals of Ecology*. 3rd edn. Saunders, Philadelphia.

Paltridge, G. W. 1975. Global dynamics and climate – a system of minimum entropy exchange. *Quarterly Journal of the Royal Meteorological Society*, **101**, 475–484.

Rauch, J. N. & Pacyna, J. M. 2009. Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles. *Global Biogeochemical Cycles*, **23**, GB2001. http://dx.doi.org/10.1029/2008GB003376

Sassoon, R. E., Hermann, W. A., Hsiao, I-C., Miljkovic, L., Simon, A. J. & Benson, S. M. 2009. Quantifying the flow of exergy and carbon through the natural and human systems. *In*: Collins, R. T. (ed.) *Materials for Renewable Energy at the Society, Technology Nexus. Materials Research Society Symposium Proceedings* 1170E, 1170-R01-03.

Schneider, S. H., Semenov, S. *et al.* 2007. Assessing key vulnerabilities and the risk from climate change. *In*: Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E. (eds) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, 779–810.

Scott, J. C. 2010. *The Art of Not Being Governed*. Yale University Press, New Haven.

Sessions, A. L., Doughty, D. M., Welander, P. V., Summons, R. E. & Newman, D. K. 2009. The continuing puzzle of the great oxidation event. *Current Biology*, **19**, R567–R574. http://dx.doi.org/10.1016/j.cub.2009.05.054

Smil, V. 1999. Detonator of the population explosion. *Nature*, **400**, 415.

Steffen, W., Grinevald, J., Crutzen, P. & McNeill, J. 2011. The Anthropocene: conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A*, **369**, 842–867. http://dx.doi.org/10.1098/rsta.2010.0327

US CENSUS BUREAU 2012. *International Programs, World Population, Historical Estimates of World Population*. http://www.census.gov/population/international/data/worldpop/table_history.php

Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H. & Matson, P. A. 1986. Human appropriation of the products of photosynthesis. *BioScience*, **36**, 368–373.

Vitousek, P. M., Mooney, H. A., Lubchenco, J. & Melillo, J. M. 1997. Human domination of Earth's ecosystems. *Science*, **277**, 494–499. http://dx.doi.org/10.1126/science.277.5325.494

Vorosmarty, C. J., Meybeck, M., Balazs, F., Sharma, K., Green, P. & Syvitski, J. P. M. 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change*, **39**, 169–190.

Werner, B. T. 2003. Modeling landforms as self-organized, hierarchical dynamical systems. *In*: Wilcock, P. R. & Iverson, R. M. (eds) *Prediction in Geomorphology, Geophysical Monograph Series*. American Geophysical Union, Washington, **135**, 133–150. http://dx.doi.org/10.1029/135GM10

Wilde, S. A., Valley, J. W., Peck, W. H. & Graham, C. M. 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature*, **409**, 175–178. http://dx.doi.org/10.1038/35051550