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GEOBIOLOGY OF THE ANTHROPOCENE

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22.1 Introduction

Homo sapiens first appeared on the Earth somewhere in Africa roughly 200 000 years ago. It happened with little fanfare; few could have imagined that this new species of primate would someday disrupt the Earth system to the point of defining a new geologic epoch around its legacy. Indeed, the first 150 000 years of the natural history of our species, mostly in Africa, were fairly uneventful for reasons still not well understood. But then, with migration out of Africa, things started to change. Having mastered new hunting skills, humans began to perturb their ecosystems, first by overhunting large animals, which also deprived rival predators of adequate food supplies. Then with the development of agriculture in the last 10 000 years, humans began an appropriation of the Earth's surface for food, fuel and fiber that continues to this day. More recently, the industrial revolution, spurred on with cheap, abundant energy from fossil organic carbon, made humans major players in Earth's geochemical cycles, including nitrogen and carbon. The latter now threatens to end the Pleistocene glacial cycles and return the Earth to a state not seen for 35 million years. The future of human interactions with the Earth system remains uncertain, but the impact of human actions already taken will last for more than 100 000 years. Avoiding massive disruptions to geobiological systems in the future is likely to require, ironically, even larger interventions by humans through advanced technology, the final step in a transition to the engineered epoch of Earth history.

22.2 The Anthropocene

The adoption of the term 'Anthropocene' is commonly credited to Paul Crutzen, the Nobel-prize winning chemist, in a speech in 2000, although the recognition of human impact on the Earth and the declaration of a new geological epoch long precedes Crutzen (Zalasiewicz *et al*., 2011). Already in 1871, Italian geologist Antonio Stoppani used the term 'Anthropozoic' to describe 'new telluric force, which in power and universality may be compared to the greater forces of earth.' Joseph LeConte, in his *Elements of Geology* (1878) uses the term 'Psychozoic' to describe the age of man, characterized by the 'reign of mind.' Even Charles Lyell pondered the enormous impact that humans were having on the Earth, for he recognized that some might see in it a challenge to his arguments about the uniformity of nature's laws. In the original version of his *Principles of Geology* (1830), Lyell discusses the modern origin of humans, and the question of

> 'whether the recent origin of man lends any support to the same doctrine, or how far the influence of man may be considered as such a deviation from the analogy of the order of things previously established, as to weaken our confidence in the uniformity of the course of nature.'

Lyell states his concern clearly:

> 'Is not the interference of the human species, it may be asked, such a deviation from the antecedent course of physical events, that the knowledge of such a fact tends to destroy all our confidence in the uniformity of the order of

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nature, both in regard to time past and future? If such an innovation could take place after the earth had been exclusively inhabited for thousands of ages by inferior animals, why should not other changes as extraordinary and unprecedented happen from time to time? If one new cause was permitted to supervene, differing in kind and energy from any before in operation, why may not others have come into action at different epochs? Or what security have we that they may not arise hereafter? If such be the case, how can the experience of one period, even though we are acquainted with all the possible effects of the then existing causes, be a standard to which we can refer all natural phenomena of other periods?'

In the early 19th century, Lyell already recognized the magnitude of human impact on the Earth system.

'When a powerful European colony lands on the shores of Australia, and introduces at once those arts which it has required many centuries to mature; when it imports a multitude of plants and large animals from the opposite extremity of the earth, and begins rapidly to extirpate many of the indigenous species, a mightier revolution is effected in a brief period, than the first entrance of a savage horde, or their continued occupation of the country for many centuries, can possibly be imagined to have produced.'

One can only imagine what Lyell would think were he to see the scale of human activities today.

Lyell's argument was that humans – even with their disruptions to natural ecosystems, even with their morality and their unique ability to interpret nature through an understanding of its natural laws – remain bound by those laws. This is what allowed Lyell to preserve his uniformitarian theory, which he viewed as essential for understanding Earth history. But there are closely related questions looking to the future that Lyell did not address. Is the Anthropocene (to use the modern form) recognizable among other geological epochs? When did it begin and when will it end? And what, among all the many features of the geobiological record of the Anthropocene, will be most recognizable millions of years in the future? In this chapter, I describe some aspects of the geobiology of the Anthropocene in an attempt to address these questions.

22.3 When did the Anthropocene begin?

In a 2000 newsletter of the International Geosphere-Biosphere Program, Crutzen and Stoermer suggested that the transition from the Holocene to the Anthropocene began near the end of the 18th century, coincident with the invention of the steam engine by James Watt (1784) and the rise in greenhouse gases observed in ice cores (Crutzen and Stoermer, 2000). A different view comes from William Ruddiman, who argued that human interference in the climate system began 7000 years ago with the development of agriculture. Ruddiman pointed to the concentration of atmospheric CO_2, which was 260 ppm approximately 8000 years ago, and suggested that it should have fallen by 20 ppm, synchronous with changes in the Earth's orbit around the sun, as it had during previous interglacials Intervals. Instead, atmospheric CO_2 rose to 280 ppm prior to the industrial revolution, a net difference of 40 ppm that Ruddiman attributed to the release of carbon dioxide from deforestation. It is this reversal of greenhouse gases, Ruddiman claimed, that stabilized the climate of the Holocene and allowed human civilizations to flourish (Ruddiman, 2003, 2007).

Examination of the carbon cycle does not support Ruddiman's hypothesis. Over thousands of years, most of the carbon released from deforestation would dissolve in the ocean, which means that a net change in atmospheric CO_2 of 40 ppm would require roughly 600 billion tonnes of carbon to be released from the land, an amount equivalent to the entire modern terrestrial biosphere. Moreover, such a large release of carbon from biomass would change the isotopic composition of carbon reservoirs, as recorded in shells and ice cores; no such change is observed. Finally, the rise in atmospheric CO_2 has been linear over the last 7000 years, but the expansion of agriculture was not. It seems most likely that early agriculture had a smaller impact on the carbon cycle than Ruddiman claimed.

But that is not to say that early humans had little effect on their environment. It is quite clear that early humans changed their ecosystems by overhunting of large animals long before the invention of agriculture (Alroy, 2001). The extinction of larger mammals and birds in Asia, Europe, Australia, the Americas, and New Zealand and the Pacific Islands immediately followed the spread of human populations across these regions. The timing of the extinctions is diachronous, as predicted by the over-hunting hypothesis; moreover, the disappearance of large animals is a distinctive feature of the extinction across every climatic regime, from the tropics to the temperate zones, and in both hemispheres, refuting a climatic explanation for the extinction as some have proposed. Only in sub-Saharan Africa did megafauna survive the rise of human society, and the reason for their persistence remains a mystery.

In *Guns, Germs and Steel* (Diamond, 1997), Jared Diamond proposed that the co-evolution of African megafauna with humans, as well as with earlier hominids, allowed large mammals to survive – the essential claim is that large animals in Africa learned to be afraid of humans, a behaviour honed by natural selection. This hypothesis predicts good news for future conservation efforts as it suggests that African megafauna have an instinctive key to their own survival – i.e., their fear of humans. An alternative explanation, however, allows less optimism. It seems possible that large mammals in Africa survived not because of co-evolution with humans, but because human occupation of sub-Saharan Africa was never expansive enough to drive these animals to extinction. Tropical diseases, such as malaria and sleeping sickness, are virulent in sub-Saharan Africa, (e.g. Greenwood and Matabingwa, 2002). Perhaps it was the co-evolution of mosquitoes and humans rather than megafauna and humans that prevented human populations in sub-Saharan Africa from reaching a critical level to drive large animals to extinction. If so, it does not bode well for the future of African megafauna, as their demise may be the unintended consequence of modern efforts towards economic development and poverty alleviation.

So, then, what do we identify as the beginning of the Anthropocene? If we define it as the first large impact of humans on the environment, then the megafaunal extinctions provide an excellent candidate. A thorn for stratigraphers, however, is that these extinctions are diachronous across many different regions. A more serious objection is that the extinctions themselves do not foreshadow the extent of human dominance over the Earth system. If the megafaunal extinctions were the major environmental impact over the history of human society, it is not clear that this would rise above the threshold for defining a new geologic epoch; it might only be seen as an ecological bottleneck of some sort. As I will discuss below, human society following the industrial revolution, facilitated by fossil carbon as an energy source, has changed the Earth system in a way that almost challenges Lyell's confidence in the uniformity of nature's laws. One can see this change using many different metrics: economic output, population, energy consumption – all begin to grow exponentially starting in the late 18th century. Of course, earlier events of human history contributed to this accelerated growth, from the classical civilizations of Egypt, Greece and Rome, to the technological achievements of the European renaissance. But if one wants to identify the launching point when humans started down an irreversible path towards a complete transformation of their planet, then Crutzen's choice of 1784 seems appropriate.

22.4 Geobiology and human population

From the time of the Roman Empire until the start of the 18th century, the human population hovered somewhere between 100 million and 1 billion. Around the start of the Anthropocene, it reached 1 billion; by 1930, 2 billion; and, in 1974, human population reached 4 billion. It sits now very close to 7 billion, and most demographic projections predict a peak around 9 billion sometime in the middle of the 21st century. How Earth's ecosystems will fare on a planet with 9 billion human beings is a question we will address here.

Beginning with Thomas Malthus, many have prophesied grimly about how population growth will disrupt human society. The modern version of Malthusian catastrophism is epitomized by *The Population Bomb*, written in 1968 by Paul Ehrlich. In this book, Ehrlich made a series of dire predictions for the near future; for example, he argued that India would not be able to feed 200 million more people by 1980. In general, Ehrlich's predictions have not been accurate; India's population today is nearly 1.2 billion, and it has become the world's largest exporter of rice.

The major reason why Ehrlich's predictions were wrong is the technological innovation in agriculture, commonly referred to as the Green Revolution. Working in Mexico in the 1950s, Norman Borlaug and colleagues developed high-yield varieties of wheat that were resistant to many diseases. When combined with modern agricultural production techniques, these new strains increased wheat yields in Mexico from less than 1 tonne per hectare in 1950 to nearly 5 tonnes per hectare in 2000. India and Pakistan experienced smaller increases in yields, but still enough to make them self-sufficient – something Ehrlich had not envisioned in 1968. Borlaug's approaches were later applied to other crops, including several types of rice. Another component of the Green Revolution involved the industrial production of nitrogen fertilizer, discussed below, and the mining of phosphate that allowed modern industrial agriculture to develop around the world. Overall, the Green Revolution allowed the world's population to grow far beyond what Ehrlich had estimated as the Earth's carrying capacity.

Some take the example of the Green Revolution as proof that there are no environmental constraints on human population, and that Ehrlich's entire approach was wrong. Another perspective is that Ehrlich may have been wrong in his specific predictions, but perhaps only about the time scale; the challenge of exponential population growth in a world with finite resources still exists. In his acceptance speech for the Nobel Peace Prize in 1970, Norman Borlaug warned,

> 'the green revolution has won a temporary success in man's war against hunger and deprivation; it has given man a breathing space. If fully implemented, the revolution can provide sufficient food for sustenance during the next three decades. But the frightening power of

human reproduction must also be curbed; otherwise the success of the green revolution will be ephemeral only' (Borlaug, 1970).

It is true that the growth rate of world population has dropped – much of it due to economic development that leads to a 'demographic transition' in many countries, that is, that women choose to have smaller number of children as their income rises, especially if they are not deprived access to education and employment. But even with a lower growth rate and population stabilization by 2050, it is not clear whether the Earth can support 9 billion people without a large fraction of that population suffering from limited access to food and water. One can ask whether the Green Revolution saved hundreds of millions of people from starvation only to condemn billions of people to a similar fate sometime in the future. Borlaug was keenly aware of the future challenges brought on by a growing population, as well as the increased consumption of meat due to greater affluence in many populous regions of the world. He predicted that we would need to double the world food supply by 2050, and saw this challenge as a major priority for research efforts today. It remains an open question whether the increase in crop yields provided by Borlaug's efforts will continue to grow through genetic modification of plants, especially in the face of human-induced climate change.

In *How Many People Can the Earth Support?* Joel Cohen (1996) examined the full range of constraints on human population including land area, food production, fresh water, and energy. He also explored the history of different ideas of what the carrying capacity of the planet might be. In the end, Cohen concluded that his title asked the wrong question, as the maximum number of people only makes sense if one specifies level of affluence, extent of equality, or the number of people who are allowed to suffer from malnutrition and other impacts of extreme poverty. In Cohen's framing, the statement about the Earth's carrying capacity is a statement about one's values concerning the human condition. Within that framing, one can take a Malthusian perspective that emphasizes exponential population growth in the face of resource limitations or a Borlaugian perspective that emphasizes technology's capacity to remove or at least soften those environmental constraints. We will return to the question of technological innovation below.

The focus of this chapter, involves the impact of human population on the Earth system. We are interested not only in how humans will fare as their population grows, but how 9 billion humans will affect the rest of the geobiological system. The two issues are related, as human societal disruption such as war or famine has its own substantial environmental impacts. However, one can ask how the Earth system will respond to a growing population, and how much of the expected change is actually driven by population itself without answering the moral and ethical questions raised by Cohen. To examine this, it is useful to employ the framework of Paul Ehrlich and John Holdren in their 1971 paper on the *Impact of Population Growth* (Erlich and Holdren, 1971). Ehrlich and Holdren introduced a simple equation: Impact = Population × Affluence × Technology (IPAT) to evaluate the causes of environmental disturbance. At its core, IPAT is a simple identity, but it allows one to identify quickly the factors (population growth, economic growth, or technological change) that are most responsible for creating or solving our environmental problems. A quick analysis of two of the largest drivers of geobiological disturbance, human land-use for agriculture and anthropogenic climate change, reveals the surprising conclusion that in the near term, population growth is not likely to be the major factor driving environmental degradation. For agriculture, the IPAT equation is: land use (area) = population × (GDP/person) × (land use/GDP). Of these terms, population is likely to grow from 7 to 9 billion over the next 40 years, or 29%. Over that same time interval, GDP is expected to grow by 200 to 400%. The technology will also change in the future, driven lower by agricultural innovations that increase crop yields, but driven higher by increases in the amount of meat in the average diet, leading to greater demand for grain as well as land for pastures.

Greenhouse gas emissions tell a similar story: the first two terms are the same, with the final term reflecting the greenhouse gas intensity of our energy systems, as well as how the demand for energy changes with our affluence. One can see from both these examples that economic growth and not population growth is the larger driver of many of our environmental challenges over the next century. The technology term in both cases is uncertain, as it could add to the problem by requiring additional resources, or could reduce human demands for ecosystem services, as in the agronomic discoveries of Borlaug. This is not to say that population growth is not at the root of our current environmental challenges; after all, it was partly the population growth over the past 200 years, growing from 1 billion to 7 billion (world GDP grew by a factor of 40 over this same period), that put the Earth in its current predicament; but the people alive today are more than enough to trigger enormous changes to the Earth system even if population remains constant but consumption continues to rise with prosperity.

22.5 Human appropriation of the Earth

Driven by growing population, by economic development, and by technological innovation fueled with fossil carbon, the scale of human appropriation of the

Earth surface is remarkable. Never before has a single species so closely managed such a vast area of the planet. Roughly 40% of Earth's land surface is used for croplands and pastures (Vitousek *et al*., 1997). Another 30% remains as forest, capturing much of the terrestrial biodiversity, although roughly 5% of that is heavily managed for human needs including timber and palm oil (Foley *et al*., 2005). Even where land surfaces are not heavily managed by humans, ecological habitats are occupied by human settlements and industries or subdivided by roads, pipelines and power lines.

The impacts of human land use for agriculture, forestry, roads, cities, and industry has been, thus far, the largest source of damage to biological diversity simply through destruction of habitat. Recent estimates by the Millennium Ecosystem Assessment claim that between 10 and 50% of well-studied higher taxonomic groups (mammals, birds, amphibians, conifers, and cycads) are currently threatened with extinction, based on IUCN–World Conservation Union criteria for threats of extinction (MEA, 2005). They conclude that 12% of bird species, 23% of mammals, 25% of conifers, and 32% of amphibians are threatened with extinction, numbers that may be conservative.

Compared with human appropriation of the terrestrial realm, the marine environment seems vast and untouchable, with many of the ocean's diverse ecosystems barely described. And yet by some measures the devastation of the marine environment is even more extensive than on land. Instead of habitat destruction or pollution as the main cause of the decline of marine ecosystems, the main culprit is overfishing (Pauly *et al*., 2003). On land, the disappearance of the terrestrial megafauna occurred many thousands of years ago; in the marine realm, it occurred over the last few centuries, so we have historical accounts of what ocean ecosystems were like before the application of modern technology to commercial fishing (Jackson *et al*, 2001). The comparisons are startling. Jackson (2008) compiled an accounting of the percent decline of more than 50 different groups of marine flora and fauna, from corals to sharks to sea turtles, measured at a variety of locations around the world. Many show a loss of more than 90%, in the relevant metric (biomass, percent cover, or catch) and nearly all have sustained losses above 50%. Jackson pointed out that population declines do not result from fishing alone, but also associated disturbances including habitat destruction that comes from trawling the ocean bottom, leaving it flattened like an undersea roadway. The enormous decline in fish populations does not necessarily imply a high extinction rate, and some biologists remain hopeful that biodiversity in the ocean would partially recover if fishing practices were relaxed and other conservation measures implemented (e.g. Lotze *et al*, 2006). On the other hand, some argue that, due to a combination of stresses that includes overfishing, pollution with nutrients and toxins, acidification, habitat destruction through trawling, and climate change, a mass extinction in the ocean is unavoidable (Jackson, 2010).

Between land and sea, the future of biological diversity looks ominous. The debate is not about whether extinctions will occur, but how many and how quickly, and whether conservation efforts can be successful. Many studies limit their scope to the next century or so, neglecting to consider the long time associated with the carbon cycle and climate change discussed below (for a longer view, see Myers and Knoll, 2001). For example, the Millennium Assessment admits that their projection 'is likely to be an underestimate as it does not consider reductions due to stresses other than habitat loss, such as climate change and pollution.'

Pollution, of which climate change may be considered a special case, may yet surpass direct habitat destruction (and hunting and fishing) as the largest cause of ecosystem decline. One way to measure the scale of human intervention in the geochemical world is to look at major biogeochemical cycles such as nitrogen, phosphorus and sulfur. (Perturbation to the carbon cycle involves the special case of climate change, which I will discuss later.) For nitrogen, the simplest approach is to consider the entry point into the biogeochemical cycle – the fixation of nitrogen gas from the atmosphere. Through the Haber–Bosch process, humans produce nitrogen fertilizer, mostly in the form of ammonia or urea, at a current rate of 9.5×10^{12} mol per year, almost as large as the 10×10^{12} mol per year fixed by marine organisms (primarily cyanobacteria; Canfield *et al*., 2010), and slightly larger than the $\sim 8 \times 10^{12}$ mol per year produced via terrestrial nitrogen fixation. Additional human sources include production of nitrogen from fossil fuel combustion as well as cultivation of legumes, primarily soybeans, which have nitrogen-fixing symbionts; each of these produces roughly 2×10^{12} mol per year. Overall, then, human production of fixed nitrogen has almost doubled the overall rate of nitrogen fixation. But this perspective underestimates the magnitude of human intervention. Over-application of fertilizer combined with deposition of nitrogen oxides from fossil fuel combustion (both coal-fired power plants and tailpipes of transportation vehicles) has had much larger impacts on specific regions, particularly aquatic ecosystems such as lakes and estuaries, where runoff can concentrate nitrogen from wide agricultural regions. 'Dead zones' in the open ocean have also been attributed to excess nitrogen discharge. Terrestrial ecosystems can also be affected as the addition of extra nitrogen can greatly upset ecosystem dynamics and inter-species competition.

The story of the phosphorus cycle is similar. Mining of phosphate-bearing rock adds roughly as much phosphorus to the global phosphorus cycle as is released from natural rock weathering (Filippelli, 2002). Like nitrogen, the impacts are highly spatially variable, most concentrated in places where release of phosphorus from fertilization or use of detergents is focused by surface waters. In addition, waste from livestock and poultry farming can concentrate the total phosphorus load from vast agricultural regions, producing devastating impacts on ecosystems downstream, including eutrophication of lakes, rivers and estuaries. Unlike fixed nitrogen, which can be produced from the limitless supply of nitrogen gas in air and depends mostly on the cost of energy required for the Haber–Bosch process, phosphorus production is a mineral resource like copper or iron, and the stability of reserves has been questioned, although phosphate ore is unlikely to be in short supply for many centuries. It is possible that a shift to lower-grade phosphate deposits will raise the price of phosphate, ultimately making agriculture more expensive, but the rate of phosphate extraction is likely to continue to increase for the foreseeable future.

The sulfur cycle has also been perturbed by human activities, primarily from the combustion of coal. In this case, defining the perturbation is more complicated. The vast majority of sulfur released from coal combustion enters the atmosphere as sulfur dioxide, where it is quickly oxidized to sulfate. Deposition occurs through various wet and dry mechanisms, but results in roughly a doubling of dissolved sulfate in rivers relative to preanthropogenic loading, mostly from sulfide oxidation during chemical weathering of terrestrial rocks (Bates *et al.*, 1992). From the perspective of the atmosphere, human activities represent an enormous perturbation to a preexisting cycle dominated by volcanic emissions (less than 10% of human emissions) and production of dimethyl sulfide by marine phytoplankton. The release of sulfur has two main impacts on ecosystems. First, oxidation of sulfur dioxide produces acid rain, which can harm terrestrial ecosystems by changing the pH of lakes and soils, possibly affecting the availability of calcium, a critical nutrient for most trees. Second, sulfate aerosols reflect sunlight, offsetting the impacts of greenhouse gases on climate. As discussed below, this unintentional climate intervention is currently masking the impact of human perturbations to the carbon cycle. In the long run, however, the sulfate aerosol effect cannot keep up with sustained release of CO_2 due to the short residence time of sulfur in the troposphere (days to weeks).

Popular awareness of pollution's impact on ecosystems in the United States can be traced to the publication of Rachel Carson's book, *Silent Spring* (Carson, 1962). Carson focused her attention on the harmful effects of pesticides on the environment, particularly on birds. She began her exposition with 'a fable for tomorrow', a prosperous, rural town in the USA that suddenly lost its birds, its blossoms, its wildlife:

> 'this town does not actually exist, but it might easily have a thousand counterparts in America or elsewhere in the world. I know of no community that has experienced all the misfortunes I describe. Yet every one of these disasters has actually happened somewhere, and many real communities have already suffered a substantial number of them. A grim specter has crept upon us almost unnoticed, and this imagined tragedy may easily become a stark reality we all shall know.'

If one takes Carson's fable in a literal sense, one could argue that her concerns over pesticide use were slightly misplaced, not because pesticides have no substantial effects on wildlife, but because chemical pollution of nature with pesticides is probably not the most harmful way that humans disturb natural ecosystems. It would be interesting to see how Carson would react today were she armed with a deeper understanding of the magnitude and duration of the global threat to ecosystems posed by human-induced climate change.

22.6 The carbon cycle and climate of the Anthropocene

Of all the biogeochemical cycles that humans have affected with industrial activities, carbon dioxide is most significant both for the scale of the disruption and the longevity of its potential impact. The famous Keeling curve, a record of carbon dioxide measured in the atmosphere at Mauna Loa, Hawaii, provides a spectacular demonstration of how the entire atmosphere is affected by human activities, primarily the combustion of fossil fuels with some contribution from deforestation and other land use changes. Viewed in isolation, the Keeling curve understates the scale of human interference. A more appropriate perspective places the Keeling data alongside longer records of atmospheric CO_2 measured in ice cores from Antarctica. Measurements of ancient atmospheric composition extracted from bubbles in the ice have now been extended back 650 000 years before present (Siegenthaler *et al.*, 2005). Over this time interval, CO_2 reached minimum levels of approximately 180 ppm during glacial maxima and peaked below 300 ppm during the interglacials. (Current atmospheric CO_2 concentration as I am writing this chapter is approximately 390 ppm, heading towards a seasonal high of roughly 395 ppm at the beginning of northern spring.) Direct measurement of more ancient CO_2 levels will not be possible unless more ancient ice is identified, but indirectly, through a variety of geochemical measurements, including carbon isotopes of organic molecules (Hendericks and Pagani, 2008), atmospheric CO_2 concentration can be estimated over much longer time scales. These data suggest that atmospheric CO_2 has not been much higher than 300 ppm for the last 34 million years.

What will be the geobiological consequences of higher atmospheric CO_2? Higher CO_2 concentrations do cause direct ecological disruption, particularly in plant communities, as some species are able to take advantage of the higher CO_2 levels by increasing rates of photosynthesis. CO_2 concentrations between 500 and 2000 ppm are unlikely to have strong metabolic effects on most terrestrial animals. In the ocean, however, as CO_2 emissions continue to outpace ocean mixing, a transient lowering of the calcium carbonate saturation state in the surface ocean, commonly called ocean acidification, will put stress on a wide variety of marine organisms, particularly – but not only – those that grow their skeletons out of calcium carbonate. Indeed, coral reefs may be greatly impacted, adding to the multiple stresses on these diverse ecosystems that additionally include overfishing, habitat destruction, runoff of excess nutrients, and warming (e.g. Pandolfi *et al*., 2005).

But there is no question that the largest impact of human perturbation to the carbon cycle will be in the disruption to the climate system. It remains uncertain exactly how much warming will occur as CO_2 levels rise, mostly due to uncertainty surrounding feedbacks in the climate system that can amplify the direct effects of higher greenhouse gas concentrations, as well as feedbacks in the carbon cycle that can add additional carbon dioxide to the atmosphere. The standard measure of the degree of amplification of radiative forcing is called climate sensitivity, defined as the change in global average temperature for a doubling of atmospheric CO_2. Most general circulation models used to predict future climate change use a climate sensitivity between 1.5 and 4 °C, based on calibration of these models to the observed temperature change over the last century. However, the last century may not be a good predictor of climate sensitivity in the future as CO_2 rises to levels far outside of the calibration period. Several possible feedbacks may only kick in during warmer climates; for example, Kirk-Davidoff *et al*. (2002) proposed that increased stratospheric water vapor due to changes in atmospheric circulation in a warmer climate might lead to enhanced warming at high latitudes in the wintertime due to optically-thick polar stratospheric clouds.

This is where the geologic record of past climate change is especially useful. The last time that we think atmospheric CO_2 was well above 300 ppm, was the Eocene (Hendericks and Pagani, 2008). A range of observations of Eocene climate, including isotopic, chemical, and paleobiological data, reveal a general picture of a very warm world, with globally averaged temperatures elevated by as much as 6 to 10 °C above the present (Zachos *et al*., 2001). For example, palm trees, plants whose fundamental anatomy makes them intolerant of freezing, grew in continental interiors at mid to high latitudes. From this, one can conclude that winters in these regions were much milder than today (Wing and Greenwood, 1993).

An important difference between the Eocene and climate change over the next few centuries is that the warm climate in the Eocene persisted for millions of years, with higher CO_2 concentrations most likely brought about by higher rates of volcanic outgassing that persisted from the Cretaceous into the Paleocene and Eocene (e.g. Berner *et al*., 1983). This means that the entire climate system as well as most ecosystems in the Eocene had time to adjust to a warm climate and reach a quasi-equilibrium state, with no ice caps at high latitudes and very warm deep ocean temperatures. In contrast, human perturbations to the atmosphere today are happening so quickly that global ecosystems may have great difficulty adapting to the transient changes.

It is common, when assessing the potential impacts of future climate change, to focus on the climate in 2100 CE, presumably because we assume that people do not care very much about climate change farther out in the future. But if one is concerned with how Earth's ecosystems will be affected on the scale of the paleobiological record of life, then we must look well beyond 2100 CE to appreciate the full impact of the rapid combustion of fossil fuels on the planet.

In a series of papers, David Archer and colleagues elegantly describe the long response-time of the carbon cycle to fossil fuel emissions (e.g. Archer *et al*, 2009). The initial rise in atmospheric CO_2 comes primarily from the fact that humans are burning fossil fuels faster than the uptake by sinks in the ocean and terrestrial biosphere. CO_2 will continue to rise until fossil fuel emissions fall below the natural sinks (Archer and Brovkin, 2008). Consider a hypothetical case in which CO_2 emissions from fossil fuels stop altogether by the end of the 21st century. Atmospheric CO_2 concentration would begin falling as soon as emissions stopped due to continued uptake, primarily by the ocean (assuming that the large stores of carbon in soils in the tundra or in tropical rainforests do not start releasing carbon faster than the natural sinks). As the amount of CO_2 dissolved in the ocean increases, the pH will drop slightly, driving the dissolution of carbonate on the seafloor as chemical equilibration is slowly achieved. After 10 000 years, this chemical exchange, called carbonate compensation, will be essentially complete, but 15 to 25% of the initial CO_2 released from fossil fuel combustion will remain in the atmosphere (Archer and Brovkin, 2008). This amount could be even larger if additional sources, such as release of methane hydrates in the ocean or release of soil carbon from the frozen tundra, were to add substantially to the carbon produced from fossil fuel combustion. Over the next 100 000 to 200 000 years, a slight increase in silicate weathering rates on land, driven by the warmer climate, would eventually convert the remaining CO_2 into calcium carbonate, with some additional uptake into marine organic carbon buried in sediments.

One can think of this residual CO_2 that requires more than 100 000 years for conversion to calcium carbonate as the long tail of human society's impact on the atmosphere. Archer and Brovkin (2008) calculate that if our cumulative CO_2 emissions are 1000 billion tonnes of carbon and released over the next 150 years, then CO_2 will rise to roughly 600 ppm, and will remain near 400 ppm for tens of thousands of years. If cumulative emissions over the next several centuries reach 5000 billion tonnes of carbon, then CO_2 will peak above 1800 ppm, and stay above 1000 ppm for tens of thousands of years. It is important to remember that this tail in the atmospheric CO_2 curve is set solely by the cumulative emissions. It is not sensitive to how quickly the emissions occur over the next millennium. To put it another way, imagine that we were able to reduce global CO_2 emissions from fossil fuel consumption to half of current levels by the middle of the 21st century, but those emissions continued over the following 1000 years as countries slowly used their remaining reserves of coal, natural gas, and petroleum, albeit at a much slower rate. The long-term concentration of CO_2 in the atmosphere in this case is almost the same as if we released that CO_2 all in this century – roughly 1000 ppm – and would remain for tens of thousands of years to more than one hundred thousand years. The only difference between these scenarios comes from the impacts of the transient, century-scale rise in CO_2 on ocean uptake through stratification, and on any potential carbon feedbacks triggered by the extreme CO_2 levels over the next few centuries.

What does this mean for geobiology? Elevated CO_2 at even 400 ppm, much less 1000 ppm, for tens of thousands of years takes the Earth system back to Eocene conditions. It is likely that both polar ice sheets will melt on this timescale; glaciologists argue over specific predictions for how quickly Greenland and Antarctica will lose ice over the next few hundred years (e.g. Vermeer and Rahmstorf, 2009), but over tens of thousands of years, there is no question that most of the ice on Greenland and much of the ice on Antarctica will disappear. The loss of ice will raise sea level by as much as 70 m, with an additional 2 to 10 m coming from the warming of the deep ocean and the thermal expansion of seawater. Disruption to terrestrial and marine ecosystems at virtually all latitudes will be enormous from the sea level rise and submersion of land areas; from changes in the hydrologic cycle, possibly including the migration of the Hadley circulation that causes subsidence and hence aridity in today's subtropical deserts; and from the temperature rise itself, which will disrupt ecosystems in all sorts of direct and indirect ways.

There is one analogy to future climate change in the geologic past that is worth consideration. At the very beginning of the Eocene, 55 million years ago, global temperature warmed by 6 °C in less than 10 000 years (Zachos *et al.*, 2001), coincident with a change in the carbon isotopic composition of seawater that is likely to have been the result of the oxidation of a large amount (i.e. >5000 Gt) of organic carbon (Higgins and Schrag, 2006); a large carbonate dissolution event at that time is the fingerprint of a large and rapid release of CO_2 (Zachos *et al*, 2005). Compared with Archer's scenarios, the Paleocene–Eocene thermal maximum (PETM) is equivalent to the higher carbon emission scenario; indeed, the carbon and oxygen isotope record in the earliest Eocene shows how the carbon cycle and the warming slowly subsided over the next 200 000 years (Zachos *et al*, 2001), just as most carbon cycle models predict a long, slow decline in CO_2 concentration following the age of fossil fuel emissions (Archer and Brovkin, 2008).

There are lessons from the PETM that may help us understand how future climate change will affect the geobiological world. By modelling the carbon cycle during this event, Higgins and Schrag (2006) showed that the CO_2 concentration in the atmosphere must have tripled or possibly quadrupled, implying a climate sensitivity of 3 to 4 °C per doubling, on the high end of what most climate models use for predicting the future. Moreover, this may be a low estimate relative to what we may see over the next few centuries because there were no ice sheets or sea ice before the PETM, and the impact of reduced albedo from melting snow and ice on Earth's temperatures over the next few centuries is likely to be significant.

One additional lesson from the PETM regarding the impact of climate change on ecosystems seems quite optimistic, at least on the surface. There is no evidence that either the abrupt warming during the PETM or the direct effects of CO_2 on calcite and aragonite saturation state of the surface ocean drove any large mass extinctions, except for benthic foraminifera (Thomas and Shackleton, 1996) that may have succumbed to acidification, low oxygen levels driven by transient stratification, or perhaps the warming itself. This does not mean that ecosystems were unaffected by the PETM. A Scuba diver observing coastal seas during the event would have witnessed a massive die-off of coral, much like one sees in the Caribbean today (Scheibner and Speijer, 2009). And many land plant species survived PETM warming by migration, a response that is complicated today by cities, croplands, roads and other barriers to migration (Knoll and Fischer, 2011). The persistence of most biodiversity implies that enough refugia existed for species to survive despite the enormous change in environmental conditions.

There are several reasons not to take this as a rosy sign for the future. First, it is possible that additional impacts of human activities, including pollution and land-use changes, in combination with stress from climate change will exceed whatever tolerance most ecosystems have for adapting to rapid changes. For example, as noted above, migration routes for species on land are constrained by roads, cities and farmland – conditions that did not exist during the PETM. Second, an important difference between the PETM and today is that the mean climate state was already quite warm in those times, and had been for tens of millions of years, as discussed above. We are heading toward such warm conditions today from a relatively cold climate. This means that all cold-dwelling plants and animals that currently inhabit polar, sub-polar and even most temperate ecosystems, as well as the many marine ecosystems that live in the colder regions of the oceans, can take no comfort from the resilience of warm-dwelling ecosystems that survived the PETM. Imposing a warmer world on ecosystems from the coldest parts of the Earth may be particularly cruel; even where the human footprint through appropriation of the land and ocean for food, fuel and fiber has been relatively mild and wilderness is abundant, such as Alaska or Siberia, climate change of the scale predicted for the next millennium means that organisms will literally have no place left to go.

22.7 The future of geobiology

In the preceding sections, I have described the enormous scale of human intervention in the Earth system. It seems likely that, as climate change compounds the impacts of human land use, pollution, and overhunting and fishing, the Anthropocene will be seen in the distant geologic future as a time of mass extinction, visible in the fossil record and coincident with evidence for a large warming event and a major marine transgression driven by the temporary deglaciation of the polar continents. One can imagine earth scientists, tens of millions of years in the future, arguing over the connection between the warming and the extinctions, and also over whether the extinction was abrupt or gradual, confused by the earlier and diachronous dates for the extinction of terrestrial megafauna. Whether the global decline in biodiversity over the next many millennia ever comes close to the enormous loss of greater than 90% of species at the end-Permian extinction (Knoll *et al*., 2007) remains uncertain because we do not know how much carbon will be emitted over the next millennium nor how severe the impacts of climate change will be. In addition, we do not understand the ecological responses to climate changes coupled with all the other stresses discussed above, nor how species extinctions will reduce the resilience of the remaining communities. These are some of the challenges for the future of geobiological research, as we attempt to understand the Earth system and the role of life in sustaining it well enough to inform engineering solutions to anthropogenic impacts. There will be greater and greater demand for such insights as predictive models calibrated to the historical record may be less and less accurate as the world departs from the range of environmental conditions that have persisted for the entirety of the human species. Of course, the outcome of our actions also depends on how humans react to the changes. This may be the true meaning of the Anthropocene, when the geobiological fate of the planet is fundamentally intertwined with the behaviour of human society.

Some have argued that the destruction of nature except for those species or ecosystems that serve some human-centred purpose will ultimately drive the collapse of human society. Some biologists and economists see a focus on 'ecosystem services' as an effective political strategy to encourage conservation and change human behaviour by articulating this possibility, but such a strategy fails to recognize how strong the demand for additional natural resources will be as human population growth and economic development proceeds. The idea that the non-marketed value of natural ecosystems will stand as a barrier to the complete appropriation of nature seems at best naïve. It is possible that humans will fall victim to the environmental destruction they have created, depending on how harmful the impacts of climate change turn out to be, but this probably underestimates the adaptability of the human species. One lesson from the first 200 years of the Anthropocene is that human technology has reduced our dependence on the natural world – or at least changed the terms of its engagement. This is not to deny the possibility that human society could destroy itself. The global nuclear arsenal, if ever used, has the power of more than 6 billion tons of TNT, less than one percent of the power of the Chicxulub impact at the Cretaceous–Tertiary boundary (Bralower *et al*., 1998), but still large enough to erase most terrestrial ecosystems. But if humans can avoid self-destruction through weapons of mass destruction, their skill at adaptation is likely to allow them to survive environmental degradation – possibly at the cost of many other species.

A more optimistic view for conservation of natural ecosystems, but in some ways a more challenging one, is that humans will not sit back and simply react to climate change and other environmental challenges, but will play an active role in engineering the Earth system to suit their needs. With respect to climate change, this 'geoengineering' has been described as an emergency option if the rate of climate change accelerated over the next few decades, or if consequences looked much worse than anticipated. Recently, such ideas have gained more prominence (Crutzen, 2006), not as a substitute for serious emissions reductions, but in the sober realization that emissions reduction efforts may not be sufficient to avoid dangerous consequences. Adjusting the incoming solar radiation through reflectors in the upper atmosphere (Keith, 2000) appears to come at a very low cost relative to other strategies of climate change mitigation (Schelling, 1996), and may be relatively effective in offsetting the most catastrophic consequences of climate change (Caldeira and Wood, 2008). Archer and Brovkin (2008) argue that, because of the long lifetime of CO_2, sustaining such an engineering system for tens of thousands of years or more is not feasible. This fails to consider that engineering the climate for a few centuries could be combined with a variety of ways of removing CO_2 from the atmosphere, albeit at relatively high cost, so that the problem was completely abated by the end of a millennium or so. Some have expressed consternation at the prospect of engineering the climate for the entire planet, but one can also see it as simply an extension of the wide variety of ways that humans have taken control of the natural world, from artificial fertilizer and pesticides, to genetically modified crops, to large hydroelectric dams that regulate water flow to riverine ecosystems.

Capturing carbon dioxide from the air and pumping it into geological respositories seems fairly straightforward, if we could find a way to do it safely and cheaply. One can see this enterprise simply as an engineering effort aimed at reversing the huge perturbations to the carbon cycle that humans have already imposed on the planet, perhaps by simply speeding up the Earth's way of removing carbon dioxide by silicate weathering (House *et al*., 2007). Removing carbon dioxide from the atmosphere is fundamentally a slow process; it would take centuries at least to reverse the carbon cycle impacts that humans have already wrought. What is different about solar radiation management is that it is immediate, which brings up a range of questions about ethics and governance. For some reason, such ethical discussions are never raised for changes imposed over longer timescales, such as climate change itself. There is no question that the power to engineer the climate to instantaneously conform to our direction comes with an awesome responsibility, although not fundamentally different than the responsibility that comes with nuclear warheads. How could we engineer the climate in a way that could be failsafe? Which countries would control this effort? Who would decide how much to use, or when? And what would happen if something went wrong, if we discovered some unforeseen consequences that required shutting the effort down once human societies and natural ecosystems depended on it?

Ironically, such engineering efforts may be the best chance for survival for most of the Earth's natural ecosystems – although perhaps they should no longer be called natural if such engineering systems are ever deployed. Those who fight for conservation of nature are faced with a remarkable dilemma. Climate change, when added to all the other human activities that threaten the natural world, has already placed the Earth on the verge of a major extinction, regardless of how effectively we reduce carbon emissions over the next century. Preventing the widespread destruction of natural ecosystems may require an engineering project that transforms the entire Earth into a managed biosphere, like the failed experiment in the Arizona desert. Nearly 50 years ago, Rachel Carson wrote in *Silent Spring*,:

> 'The 'control of nature' is a phrase conceived in arrogance, born of the Neanderthal age of biology and philosophy, when it was supposed that nature exists for the convenience of man. The concepts and practices of applied entomology for the most part date from that Stone Age of science. It is our alarming misfortune that so primitive a science has armed itself with the most modem and terrible weapons, and that in turning them against the insects it has also turned them against the earth.'

What Carson did not realize is that the concepts and practices of the industrial age far beyond 'applied entomology' have brought us to the point of no return. In the Anthropocene, the survival of nature as we know it may depend on the control of nature – a precarious position for the future of society, of biological diversity and of the geobiological circuitry that underpins the Earth system.

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