1 The Anthropocene and the Earth System

DEFINING THE ANTHROPOCENE

There are no places left on Earth that have not been affected in some way by human activity. Vast areas of the planet are being cleared to provide space both for our ever-expanding cities and for the intensive agriculture needed to support our burgeoning population. Even the supposedly pristine environment of Antarctica has been affected. Ice cores taken from the continent record human events such as the industrial revolution and the dawning of the atomic age. The composition of the very air that we breathe has been altered, largely through the addition of greenhouse gases, which are causing the planet to warm and sea levels to rise. The damage being done to the Earth's environment is profound, and it's leading to an alarming loss of the planet's biodiversity.

In fact, humans started altering our planet's environment thousands of years ago. The record of human activity is a key feature of what is currently the youngest formally recognised interval of geological time, the Holocene, which is considered to have begun about 11,700 years ago (the full Geological Time Scale can be found in Appendix 1). Starting at, or near, its base, sediments of Holocene age record increasing evidence of human activity. In parallel with the increasing human population, simple villages become cities, and small farms give way to intensive agriculture. Records of changing land use, mining, and evidence of human manufacturing – objects like ceramics and glass – all become increasingly common as we approach the present. Traces of human activity start out in localised areas and at a low level, but as we approach more recent times, they become more widespread and intense, reaching a peak in the present day.

In the early 2000s, an atmospheric chemist, Paul J. Crutzen, suggested that the change from the limited record of human influence over the past 11 thousand years to today's massive alteration of the environment implied that we have left the Holocene and entered a new geological epoch that he called the Anthropocene.[1] Both the idea and the name stuck, and in 2009, the Subcommission on Quaternary Stratigraphy (part of the international organisation that oversees changes to the Geological Time Scale) established a working group to formally decide whether the Earth had moved out of the Holocene into a new geological epoch. If they decided that it had, they were to suggest where the base of this new time unit could be placed.

The working group presented its report in 2016. They agreed with Crutzen that the shift in intensity from the low levels of human activity recorded earlier in the Holocene to the level we see all around us today warranted the establishment of a new geological epoch. The Anthropocene had passed its first official hurdle. However, there is continued discussion about where the base of this new time interval should be placed. This is a new *geological* time unit, so the base needs to be identified using criteria that future geologists will be able to see in the rock record. We are looking for a marker that is easily recognised, unambiguous, global in scope, and reflects an event that occurs everywhere on the planet at the same time. There was a strong push to put the base at the beginning of the industrial revolution. However, that varies from place to place. It began in England during the eighteenth century, then spread through Europe and into North America during the 1800s. Some parts of the globe didn't become industrialised until the mid to late twentieth century – and even today, there are areas that are not fully industrialised. A boundary like this, which has different ages depending on where you are geographically, is called

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[1] The name comes from the Greek *anthropus* meaning human, and -cene from the Greek *kainos*, translated as recent. The use of the -cene ending to an interval of geological time generally indicates that the interval is at the 'epoch' level in the time scale hierarchy.

diachronous, and it is not appropriate for a unit of the Geological Time Scale.

Another suggestion was to place the boundary at the exact moment that the Trinity atom bomb test in New Mexico was detonated. This would mean that the Anthropocene started on 16 July 1945 at precisely 11:29:21 Greenwich Mean Time. This was a good contender as a base because after this event, traces of certain radioactive isotopes that are only produced by the detonation of an atomic bomb start being recorded in sediments. And it certainly was very precise. But there is a problem; for a few years following the test, levels of these isotopes remained at a very low level and are hard to measure. However, their levels started to rise and become much more obvious in the early 1950s. This is also the time, following World War Two, when the level of human activity increased dramatically everywhere, a period referred to as the 'great acceleration'. The upshot of this is that the date that will be chosen for the beginning of the new epoch is likely to be sometime around 1950.

When, as seems likely, the Anthropocene is finally ratified as a geological epoch and formally included in the Geological Time Scale, who will use it? There are a significant number of geologists who don't like the idea at all – they either just don't see the point or object to defining an interval of geological time in advance of it happening – but I suspect that these naysayers are in the minority. As a practising palaeontologist who usually examines fossils from much older sediments, I'll probably have no need for it in my day-to-day work. Other Earth scientists, particularly those specialising in Quaternary studies, who examine lake sediments and ice cores to understand climates of the very recent past, almost certainly will. However, ultimately it doesn't matter whether or not geologists use the new epoch, because it transcends what a period of geological time is all about. It isn't just an interval of time; it is an important signal to humanity. It makes it abundantly clear that we are now living in a world of our own making, and that it is up to us to undo the environmental damage we are causing.

THE EARTH SYSTEM

The increased levels of human activity that are being used to define the Anthropocene are reflected in the serious damage being made to the planet's entire ecosystem. Thirty years ago, scientists attempting to find strategies to mitigate environmental problems would probably have studied individual parts of the planet's ecosystem separately. Physical geographers would look at the land changes, physicists the atmosphere, biologists the biota, and so on. However, so broad are the effects of human activity in recent decades that it was realised that looking at all the different parts of the planet in isolation wouldn't get us very far, and that a more holistic approach was needed. This has led to the application of what is known as *Earth System science*.

The Earth System recognises that the planet is made up of a number of reservoirs or spheres, which are linked to each other via complex feedback loops or fluxes that cycle energy, water, and various elements (including those necessary for life, such as carbon, phosphorus, and nitrogen) through the reservoirs. These fluxes ensure that a change made in one reservoir will flow through and affect the entire system. I've tried to illustrate a very simple model of the Earth System in Figure 1.1. It shows the system as comprising four reservoirs:

- The atmosphere – the sphere of gases that surrounds the planet;
- The hydrosphere – all the water, liquid and frozen, that sits at or near the Earth's surface;
- The biosphere – the Earth's thin coating of living organisms;
- The geosphere – all the rocks and minerals that make up the solid Earth.

There are more complex models of the Earth System where each reservoir is subdivided – for example, the geosphere could be split into the crust, mantle, and core, and the cryosphere (ice sheets, glaciers, etc.) could be split from the hydrosphere, and the relationships between these sub-spheres examined – but we will stick for now with the minimal version. The linking feedback loops are shown by the arrows, and again, in more complex models there are many more of

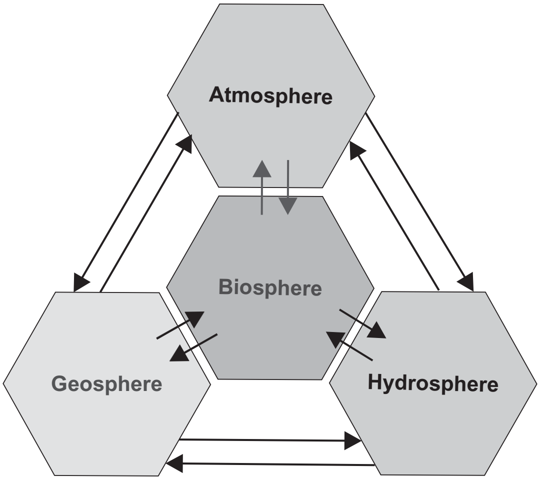

FIGURE 1.1 A very simple model of the Earth System. All the reservoirs are labelled. The arrows that join them represent some of the complex feedback loops (fluxes) that operate to maintain constant environmental conditions on Earth.

them. Although composed of separate parts, for at least the past 600 million years the Earth System has operated as a single integrated whole to keep environmental conditions on Earth relatively constant, and these conditions ensure that the planet is able to support life.

The Earth System approach developed out of James Lovelock's Gaia Hypothesis. In the mid-1960s, Lovelock suggested that we should consider the planet as a single homeostatic system that worked to maintain conditions on the planet that are suitable for life. He likened the planet to a single giant superorganism. Unfortunately, some people took this analogy literally and thought that Lovelock was claiming that the Earth was actually alive (which I don't think he was). And perhaps Lovelock should have stuck with his original name – the Earth Feedback hypothesis. Instead, he named it after a primordial Greek goddess who personified the Earth. A living planet named after the Earth Mother was never going to fly well in the scientific community, and the whole hypothesis quickly became lost in a welter of New Age waffle. But to reject Gaia completely is to throw the baby out with the bathwater: there is no doubt that Lovelock's hypothesis forms the basis of the Earth System approach.[2]

The Earth is not a single giant sentient superorganism. Instead, it's best thought of as a self-regulating machine composed of separate but interconnected parts that automatically maintain environmental conditions. However, Lovelock was right in suggesting that the Earth System does this in a way that is analogous to how a living organism maintains its internal conditions, a process called homeostasis. A simple example of homeostasis is the way you regulate your body temperature. If your temperature drops, your body responds by reducing your blood supply to exposed areas to minimise heat loss. At the same time, you start shivering, generating heat. If you get too hot, your body will try to reduce your temperature by starting to sweat. These are automatic responses to a change in your internal environment – you have no control over them. You don't consciously decide to turn on your sweat glands when you are too hot, but neither can you choose not to turn them on. The Earth System uses an automatic homeostatic-like process to maintain a set of environmental conditions that are suitable for life to exist. It's important to remember that in the Earth System, the biosphere is not simply a passive player responding to changes in the physical environment. The biosphere actively can and does participate in the alteration of the physical world in order to maintain habitable conditions on Earth.

The Earth System didn't just suddenly appear as a fully functional mechanism. As we will see, it emerged gradually, in parallel to the evolution of life on Earth. The fossil record contains spectacular examples of how the evolution of life has driven profound physical

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[2] The New Age version of Gaia as a loving Earth Mother caring for the planet has infiltrated the mainstream media. I am writing this, at home, during a lockdown caused by the Covid-19 pandemic. I have heard media commentators seriously asking if the pandemic is Gaia's vengeance for the mess we are making of the planet. No, it isn't. For that to happen, the Earth really would need to be a living, thinking organism that instructed a virus found in bats to mutate so it could transfer to pangolins, then ask it to mutate again in order to infect humans. But the planet isn't alive, and no animal plans its evolution.

changes to the environment. If evolution makes it clear that all living organisms are connected, descending from a single common ancestor, the Earth System takes this further. It demonstrates that life is intimately connected to the physical world. A complex, fully functional ecosystem has a central role to play in maintaining the equilibrium of the Earth System. To emphasise this, I have put the biosphere at the very heart of my simplified model in Figure 1.1.

The Earth System has, despite purely physical changes such as a steadily brightening Sun and tectonic upheavals, maintained planetary conditions in a state of equilibrium. This means that if it is temporarily perturbed by some sort of physical agency, such as a massive volcanic eruption that alters the environmental conditions, the system will use the automatic homeostatic processes to reverse the change and restore the original conditions. Think of it as a marble sitting at the bottom of a shallow bowl. It is in equilibrium: as long as nothing changes, it will stay right where it is. However, if you push the marble up the side, it is no longer in equilibrium. When released, the marble will try to return to equilibrium by running back down to the bottom of the bowl – in fact, it will overshoot and run back and forwards, but eventually it will settle at the base again.

An equilibrium state can change over time. A long-term perturbation – more properly called a forcing – may change the conditions to such a degree that some tipping point or threshold is exceeded, and the system cannot quickly restore the original conditions. If we go back to our marble example, it's equivalent to pushing the marble so hard that it tips over the edge and settles down in a new position – a new equilibrium state (it will probably be the floor).

In Figure 1.2, I'm showing a model of an imaginary planet's climate wobbling around one equilibrium point in response to perturbations, then shifting to another equilibrium state altogether in response to a forcing. The dashed line in the figure tracks the changes in a planet's environmental conditions through time. It starts on the left-hand side in equilibrium one. As time passes, small perturbations to the environment push the system out of equilibrium, but it quickly

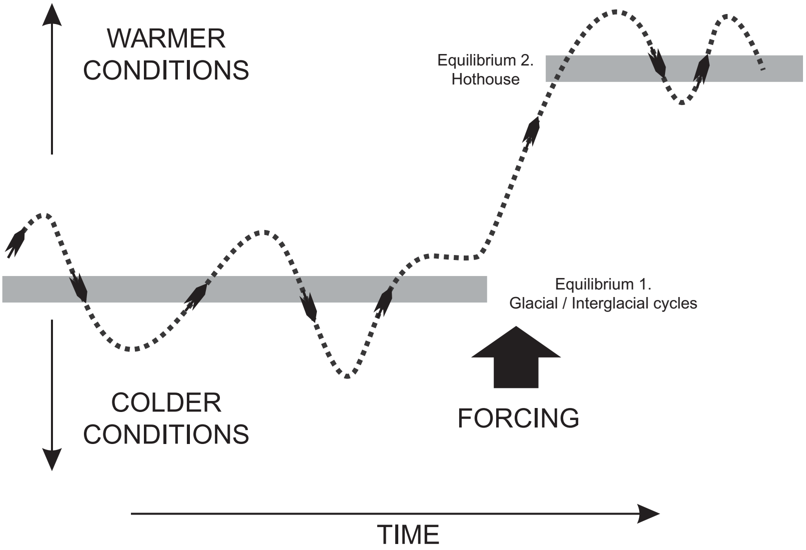

FIGURE 1.2 A cartoon of a shift in equilibrium in the planetary system. See text for explanation.

returns to its original state. I have shown the system as cycling through periods of cold and warmth; you can think of them as alternating glacial and interglacial conditions, although in my example for most of the time the planet is warm with occasional periods of cold. Note how the conditions don't always return to exactly the same state; they wobble around an equilibrium point. The large black arrow is a forcing, some significant environmental shock that pushes the system so far out of its initial equilibrium that it passes some sort of threshold or tipping point and cannot regain its original equilibrium level. In this case, a new equilibrium is established, and, in my example, the new equilibrium results in a more or less permanent hothouse set of environmental conditions. An equilibrium shift like the one shown in Figure 1.2 would cause significant changes in the planet's environment, which would be accompanied by damage to its ecosystem. In the fossil record, these shifts in equilibrium are usually accompanied by a mass extinction. If the forcing were to be removed, given enough time, the system would probably return to something like the original equilibrium point, resulting in a reduction of the planet's temperature – but that could take millions of years.

THE ANTHROPOCENE AND THE EARTH SYSTEM

I can make this more concrete by looking at how the Earth System is operating in the Anthropocene, using the carbon cycle as an example. This important biogeochemical cycle moves carbon through all the spheres that make up our simple model of the Earth System and is fundamental to maintaining life on Earth. It is also one we are currently altering significantly through our burning of fossil fuels. Figure 1.3 shows this cycle, albeit in a simple form. The black lines linking the various spheres represent the fluxes that move the carbon – either as carbon dioxide gas or as part of some other molecule – around the system. I have not included any human-induced alterations to the cycle.

Starting with the geosphere, in the absence of humans, the major source of carbon dioxide on Earth is from gases venting from

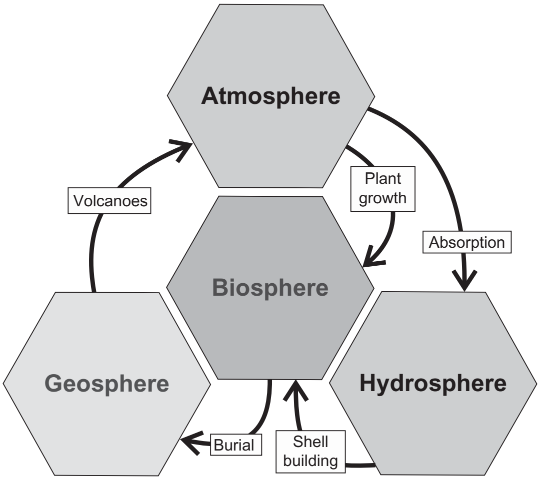

FIGURE 1.3 A simplified illustration of the relationship between the carbon cycle and the Earth System.

volcanoes. The carbon dioxide released from volcanoes enters the atmosphere, and there it plays a significant role in regulating the planet's temperature. It's a greenhouse gas, and the higher its concentration, the higher the temperature of the atmosphere. But the levels of carbon dioxide in the atmosphere don't necessarily continue to grow as volcanoes release additional gas to the system. Plants remove the gas by absorbing it as they grow, and the carbon then enters the biosphere. Atmospheric carbon dioxide is also absorbed into the waters of the world's oceans. But, as is the case with the atmosphere, the level of carbon doesn't just continue to build in the oceans; many organisms strip the carbon from the water and use it to build their shells with calcium carbonate. When plants die, the carbon moves into the geosphere as carbon-rich rocks such as coal. Similarly, when the organisms with carbonate shells die, they accumulate on the ocean floor and can be incorporated into the geosphere as limestone – locking all the carbon away.

Under pre-human conditions, the carbon cycle was kept in balance, maintaining a level of carbon dioxide in the atmosphere that ensured that the temperature on Earth stayed within a range that was suitable for life. If a sudden rise in volcanic activity caused an increase in the level of carbon dioxide in the atmosphere, the machinery of the Earth System would begin to operate to reduce the level of the greenhouse gas. This would be accomplished by an increase in both plant growth and shell production, both of which are stimulated by a rise in the carbon dioxide level. Ultimately this would lead to atmospheric carbon being removed and then locked away as coal and limestone. Once the volcanic activity faded, the amount of carbon dioxide in the atmosphere would fall, causing plant growth and shell production to slow, and the cycle would return to equilibrium. It's not a perfect system. There will be lags as the biological activity responds to an increase in carbon dioxide, so its concentration in the atmosphere will never be absolutely constant.

There is one other process associated with the Earth System that, under certain conditions, can strongly affect the amount of carbon dioxide in the atmosphere. It's not strictly part of the carbon cycle, so I haven't shown it in Figure 1.3. But chemical weathering of silicate rocks (rocks that contain high levels of silica) can have a profound effect on the level of carbon dioxide in the atmosphere. Chemical weathering is a result of carbon dioxide mixing with rainwater to produce a mild acid that attacks the surface of the rocks. As part of the chemical reaction, carbon dioxide is incorporated into the weathering products, which are then washed out into the ocean. This form of weathering can be very effective at drawing down the level of carbon dioxide in the atmosphere, but the conditions have to be right. The appropriate rocks must be available at the surface of the planet, and the climate has to be warm and wet. It also helps if the continents are in the right position on the globe. Nevertheless, as we will see, there have been occasions when chemical weathering has played an important role in the history of life.

I said earlier that Figure 1.2 showed the track of an imaginary planet. But it's actually not too far from what is happening on Earth. Starting about 2.7 million years ago, the Earth's climate has cycled through a series of glacial and interglacial periods, much as I showed in Figure 1.2. Massive ice sheets built up during the cold glacial periods and melted away during milder interglacials. The last glacial period ended at the start of the Holocene, about 11,000 years ago, and we are currently living in an interglacial. If conditions had continued as they had for the past 2.6 million years, we might expect that the Earth would cool and slip into another glacial period. But humans have changed all that.

Gathering pace during the Holocene and exploding into the Anthropocene, human perturbation of the system has been growing, and it's approaching the level of a forcing with the potential of pushing the system through a tipping point. Land clearance, habitat destruction, and forced extinctions are damaging the biosphere, lowering diversity. By burning fossil fuels, we are releasing the ancient carbon that was absorbed by plants and locked away in the geosphere. This has resulted in a rapid increase in the level of carbon dioxide in the atmosphere and, as a result, the globe is warming. The feedback loops, which under normal conditions would bring the system back into equilibrium, are struggling. Plants cannot use the carbon dioxide fast enough. We are compounding the problem by damaging the biosphere through land clearances. This results in a build-up of carbon dioxide in the atmosphere, raising the planet's temperature. Our oceans are absorbing huge amounts of the gas, but as a result their waters are becoming more anoxic and acidic, limiting the ability of shell builders to remove the excess carbon. If we don't take urgent action to reduce the human-induced forcing and allow the biosphere to heal, we may push the system past a threshold from which there is no going back. If we were to allow an equilibrium shift to occur, it would bring with it an entirely new set of very much warmer conditions and – as we will see later – increase the possibility of a mass extinction.

THE ANTHROPOCENE DEFAUNATION

So, how much damage are we doing to our biosphere? Some estimates of Anthropocene extinctions suggest that we are losing between 11,000 and 58,000 species annually. Biologists researching these extinctions have established that the primary drivers are habitat reduction through changing land use, and the introduction of invasive species. However, as well as causing extinctions, these twin drivers can cause a reduction in the population size of those species that do survive, putting them under severe threat of extinction. Biologists have coined a new word for what is happening to our biota during the Anthropocene – defaunation. This term is broader than just the extinctions on their own. It includes all the extinctions together with the many species that are under severe threat of extinction.

The estimate of an annual species loss of between 11,000 and 58,000 is extremely broad. Can't we be more precise? Unfortunately, that's not possible. It is very hard to pin down exactly how bad the Anthropocene defaunation is. This is a result of our astonishing lack of knowledge about the Earth's current biodiversity. We don't even know how many species live on our planet! In this book, I am using an estimate of 8.7 million species alive today. It is, however, only one estimate among many. While most reasonable estimates range from 2 million to 10 million, some outliers get as high as 100 million. This fundamental gap in our knowledge of the planet's biodiversity is compounded by the fact that only a small fraction of living species – only about 20%, by some estimates – has been formally described. Because we need to know that a species exists before we can decide whether it's extinct or threatened, our evaluation of the consequences of the Anthropocene defaunation has to be based on that 20%. One thing we can say, with a fair degree of certainty, is that many species have either gone extinct or are under severe threat of extinction before we had a chance to describe them. We just don't know how many species are involved – but it does mean that any estimate we make of the scale of Anthropocene defaunation will be an underestimate, probably a large one.

The situation isn't entirely hopeless; there are some data available. The Red List[3] is an attempt to assess the level of the threat of extinction of every species on the planet. Again, we must keep in mind that the conservationists who assess the data for the Red List are limited to published species, and this is usually only a very small percentage of known species. In Table 1.1, I have assembled extinction/threat data on several large groups of animals. The first column lists the number of species that have been assessed for the animal groups, with the approximate proportion of species that have been assessed shown as a percentage. In the case of mammals, birds, amphibians, and cephalopods (a group that includes octopuses, squids, and cuttlefish), just about all of the recognised species have been assessed. In the reptiles, well over half have been assessed, but for the remaining groups the data are poor to very poor. The state of

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[3] The Red List is an amazing resource. Managed by the International Union for Conservation of Nature, it can be found at http://www.iucnredlist.org/

Table 1.1 *The Anthropocene defaunation*

See text for details. Data from the IUCN Red List of Threatened Species (IUCN 2020).

Taxon	Number of species assessed (% of described species assessed)	Extinct and extinct in the wild (%)	Extinct, extinct in the wild, and threatened (%)
Mammals	5,899 (91%)	1.46	23.48
Birds	11,147 (100%)	1.47	14.80
Reptiles	7,833 (70%)	0.42	18.37
Amphibians	6,892 (84%)	0.54	33.56
Insects	9,793 (1%)	0.65	19.23
Bivalves	801 (6%)	4.00	29.09
Gastropods	7,221 (9%)	3.89	32.54
Cephalopods	750 (90%)	0	0.67
Corals	864 (40%)	0	26.85

threat for the insects is particularly badly understood, with less than 1% of species assessed.

During the rigorous assessment process used by the Red List, species are assigned to one of a number of categories depending on the level of threat. Categories range from extinct through to under no threat at all. The categories we are interested in here are: *extinct* – species that we are absolutely confident no longer exist; *extinct in the wild* – species that only exist in zoos, reserves etc; and *threatened*, which includes the subcategories of critically endangered, endangered, and vulnerable. The second column in Table 1.1 shows the percentage of known species that are either extinct or extinct in the wild. The final column adds the threatened category to the extinct and extinct in the wild column – making it a measure of defaunation.

So, based on the Red List data, how bad is the Anthropocene defaunation? Looking first at the extinct and extinct in the wild column, and even given that the values are almost certainly underestimates, the current situation doesn't look too dire. Estimates of extinction range from 0% (corals and cephalopods) to about 4% (bivalves and gastropods). But to understand our situation fully, we need to look at the whole picture and include the threatened species. Then, with the exception of the cephalopods (for which less than 1% of species are under threat), the situation gets a lot worse. In the other animal groups listed, combined estimates of extinct and threatened species range from 14.8% (birds) up to a whopping 33.56% (amphibians). I find it appalling that nearly 20% of insect species are under threat when only about 1% of known species have been assessed.

Should we worry about this level of biodiversity loss? Some people believe that we needn't. In an opinion piece, entitled 'We don't need to save endangered species. Extinction is part of Evolution' (with a subtitle of 'The only creatures we should go out of our way to protect are *Homo sapiens*') published by the Washington Post in 2017, biologist R. Alexander Pyron suggested just that. He argued that we shouldn't worry about the current wave of extinctions; there have been other mass extinctions in the past, and life made it through. He suggested that the clearing of the ecological deck by a mass extinction could be considered a good thing, allowing evolution to experiment with new forms that would eventually add to biodiversity. Critics wasted no time in telling Pyron that he was wrong, pointing out how important a diverse biota was to the planet.[4] In fact, biodiversity has been described as a central component of the Earth's life support system, underpinning the Earth's entire ecosystem. Our very existence depends on a healthy level of biodiversity. Here's why.

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[4] Pyron himself later admitted that he was wrong, and in a post on his lab page, he explains that he did sensationalise his argument, and because it was only a short piece, it came out all wrong. He also points out that he didn't choose the title of the article. In fact, he sets out his strong support for the broad conservation of biodiversity. It's called 'Statement on Biodiversity Conservation', and you can find it at http://www.colubroid.org/

While we rely on only a limited number of domesticated plant and animal species for our food supply, they in turn depend upon a host of wild species. Plants, fungi, and bacteria help maintain the soil's fertility, and many species of insects ensure pollination. In Europe, a decline in the numbers of insect pollinators has been directly linked with a significant reduction in the abundance of some plant species. The loss of some small vertebrate species has resulted in whole ecosystems being damaged. We rely on a diverse biota to maintain the quality of water in rivers and lakes, and it can also help strip pollutants out of the atmosphere. Human health is directly affected, as new medicines are very often derived from a diverse array of plant and fungi species. Future medicines might rely on species that we haven't even found or described yet, plants and animals that in the meantime might go extinct.

Perhaps more importantly, a fully functioning ecosystem is a key part of the Earth System. Many of the feedback loops that we rely on to maintain the Earth's environmental conditions cycle elements such as carbon, nitrogen, and phosphorus, all of which are vital for life, through the biosphere. For the biosphere's key role in the Earth System to be effectively carried out, we need a healthy biosphere supporting a diverse ecosystem. The Anthropocene defaunation is as much a destabilising forcing on the Earth System as the addition of greenhouse gases to the atmosphere.

Beyond the direct physical benefits that biodiversity provides for humanity, there is the simple unadulterated joy of walking through tropical rainforests, diving on a coral reef, or walking along the bank of a stream and seeing a beautiful diverse ecosystem in action. It's good for the soul.

HISTORY IS IMPORTANT

The Anthropocene defaunation doesn't exist in isolation; it is part of a longer history of biodiversity that started some 3.7 billion years ago. Today we have the tools to extract this history from the fossil record and lay it out in some detail. If we want to avoid or mitigate the worst of the environmental problems facing us, then this history is important. It can shed light on our somewhat precarious position and offer some indication of what the future holds for life on Earth. Through it, we can examine the response of ancient biotas to significant shifts in the Earth System. We can look in detail at ancient mass extinctions. Do they look similar to the Anthropocene defaunation? Were these extinction events restricted to one specific area or did they affect the entire globe? How does the biosphere recover from a mass extinction? The understanding we can gain through a detailed look at the fossil record can help us plan for what may happen in the future. We are forcing change onto the Earth System, and the fossil record contains information that shows us just how resilient the Earth System is to change – how far can it be pushed without it shifting to a new equilibrium state, triggering a mass extinction?

However, there are limitations to documenting and understanding this history, most of which are due to the vagaries of our source material, the fossil record. If we are to understand what these limitations are and why the record imposes them, we need to take a short detour and spend some time reviewing the record's strengths and weaknesses. In particular, we need to understand how fossils provide a record of biodiversity.

The other important issue we need to come to grips with is time. Not the everyday time of daily use, the getting up at 6:30, work by 9:00, home at 5:30 and bed by 11:00 sort of time; I'm talking about billions of years of geological time (I prefer the evocative term 'deep time'). We will need to understand the way that geologists use deep time and the development of the Geological Time Scale. Dealing with the enormity of deep time does take some getting used to. There are some huge numbers involved. Life appeared on the planet about 3.7 billion years ago.[5] This is a staggeringly big number. Even a million is

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[5] There are geochemical hints that life actually appeared before this, leading some workers to suggest that life reaches back beyond 4 billion years – an even bigger number!

hard to grasp – to help get the size of these numbers across to my first-year classes, I estimated how long it would take me to count to 1 million. The surprising answer was that it would take about 33 days of non-stop counting (no eating, no sleeping) to reach 1 million. To count to 3.5 billion would take around 290 *years* of non-stop counting.[6] I'll cover both of these topics in the next chapter.

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[6] If you're interested in how I arrived at this estimate, I've outlined it in Appendix 2.