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Introduction

We are probably living in the newest period of geological time, the Anthropocene. This interval of time is in the process of being formally established by the geological community to reflect the extraordinary impact that humans have had on the planet. Future geologists will examine rocks of Anthropocene age and, preserved in them, will recognise the massive changes to the planet's ecosystem brought about by human activity. They will find the remains of huge mega-cities and the debris of manufacturing. The sediments will clearly show immense changes in land use, with forests and grasslands abruptly giving way to the intensive agriculture needed to feed an exploding population. Their sophisticated geochemical analyses will show how the planet underwent rapid warming, the result of humans injecting excess carbon dioxide into the atmosphere. Future palaeontologists will note a significant shift in the fossil record. In older sediments deposited prior to the Anthropocene, they will recover fossils reflecting a diverse mammal fauna. But that will change as we enter the Anthropocene. Here, the rocks will yield a mammal fauna much less diverse than the one that preceded it. Not only that, but the fauna will be dominated by fossils of domesticated stock – sheep, pigs, and cattle. And this loss of diversity won't be confined to mammals. The record will show a massive loss of biodiversity across all biotic groups in response to deteriorating environmental conditions.

Today we are at the start of that crash in biodiversity. Species are going extinct at an ever-increasing rate. But to appreciate the full impact of human activity on the planet's biota, we need to look beyond simply the number of species going extinct. We must add to it the even larger number of species that are under severe threat of extinction. Biologists have come up with a new word for this combination of extinction and threat – *defaunation.*[1]

But today's defaunation event is not the first time that the planet's biodiversity has crashed; it's not even the first one that humans have been implicated in. It has been suggested that on up to nineteen previous occasions, large parts of the planet's ecosystem have been lost. These ancient events are called mass extinctions and are, in turn, just part of a vast history of biodiversity that begins with the appearance of the first living cell about 3.7 billion years ago.

Our primary source for the history of biodiversity is the fossil record, the remains of past organisms contained in sedimentary rocks. The extraction of this history from the fossil record is difficult. Some aspects of the record are problematic, which limits our understanding: for example, it is biased towards marine animals with hard parts such as shells. Nevertheless, the study of the deep history of biodiversity has consumed the careers of many palaeontologists and other Earth scientists. And, despite the limitations imposed by the record itself, they have been able to document, often in detail, the rollercoaster ride that biodiversity has taken over those millions and millions of years: explosive radiations as evolution explores new ecological niches and the horrendous crashes that result from mass extinctions.

The planet on which life first emerged is a vastly different one from the one we find ourselves on today. At about the time that life first appeared, the Earth's thin primordial crust had started to differentiate. Like curdling milk, rocks containing abundant lighter elements, such as oxygen and silica, separated from rocks dominated by heavier elements, like magnesium and iron. The lighter rocks coagulated together into thick clumps, the cores of what would become today's continents. The rocks made of heavier material formed the crust that

[1] It's important to note that despite the use of the word 'fauna' in defaunation, I do include plants (flora); I use it to refer to the planet's entire biota. I tried to invent a new term, one that encompassed all life, but every one I came up with sounded wrong.

makes up the floors of today's oceans. There were oceans on the early Earth as well, separating the nascent continents. They were filled with water, probably transported to the planet largely by comets. Volcanoes spewed forth massive amounts of toxic gases into the thin atmosphere, which was dominated by nitrogen, methane, and ammonia, with little or no free oxygen. On the early Earth, the Sun was less intense, but temperatures still reached up to 70 °C. The planet spun on its axis faster – each day was shorter than today.

Yet this violent, unpleasant landscape was home to our ancestors. They may have been only simple cells, but one of them, just one of them, is the ancestor of all life on Earth. That cell was successful at surviving, so it was able to produce descendants. Some of that first generation in turn were able to give rise to another generation, developing a thread of organisms, each a survival success, linking each generation through time. That first single thread linking one successful organism after another was just the start; given time and evolution, new species appeared, and the thread split. And it split again and again, as the development of the Earth's ecosystem began, and biological diversity rose.

It took a while for life to progress beyond the level of a single cell. But about 600 million years ago, multicellular life evolved. This step-up in complexity from single cells to multicellular animals coincided with an increase in the level of available oxygen. However, as we will see, the history of oxygen is complex. We do know that the tell-tale geochemical signature of the persistent presence of oxygen in the atmosphere is first seen in rocks that are about 2.45 billion years old. However, all the indications are that between 2.45 billion years and 600 million years ago the level of oxygen remained very low. Then, just as the first multicellular organisms appeared, the level of oxygen started to rise. This isn't a coincidence; complex life needs higher levels of oxygen to live. What is surprising is that the evolution of complex life did not meekly follow the steady increase in oxygen. It's more likely that the increasing complexity of life altered the environmental conditions, allowing the oxygen to accumulate.

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The first multicellular organisms on Earth were life in slow motion – a sluggish, passive affair, where strange animals were filter feeders firmly attached to the sea floor, grazers slowly eating their way across ubiquitous algal mats, or stationary quilted forms that simply absorbed nutrients directly from the ocean. Then, about 550 million years ago, all hell broke loose, and biodiversity exploded. The oceans rapidly filled with new creatures, and most of the major animal groups suddenly appeared. For over 20 million years, the level of biodiversity increased at a rate that has never been matched since. Life started to move, and we can now recognise animals that crawled across the sea floor and some that burrowed into it. Others left the sea floor behind and swam. Among these were the planet's first predators. For the first time in Earth's history, we can recognise a whole complex ecosystem. It only took about 3 billion years to appear.

But life wasn't the only thing evolving: the planet itself was changing. Its atmosphere, oceans, and rocks were being transformed, often in response to the appearance of ever more complex organisms. This transformation of the planet is part of the development of the complex mechanism that is responsible for maintaining environmental conditions on Earth. More importantly for us, it maintains conditions that are suitable for the continuation of life on Earth. This automatic climate control mechanism is called the Earth System, and life has not been a passive player in its development. The evolution of increasingly complex organisms has fundamentally altered the physical make-up of the planet. The story of oxygen, which we will discuss later, is a great example of the link between physical processes and life. The Earth System existed in a rudimentary form for the first 3 billion years of the planet's history. But it wasn't until about 550 million years ago, at the same time as the burst of diversity and the appearance of the first complex ecosystems, that the Earth System became fully operational. Since then, the system has, sometimes against all the odds, and often not perfectly, maintained a relatively constant set of environmental conditions on Earth.

What caused that explosion of biodiversity 550 million years ago that ushered in a fully functioning Earth System remains unclear. It's possible that the level of oxygen reached some critical threshold, or there was a sudden increase in the supply of nutrients to the ocean. It could even be something as simple as the development of hard parts, which opened new evolutionary opportunities and made the preservation of these animals as fossils so much easier. Whatever it was, it came with a bonus – a much-improved fossil record. The biases inherent in the record didn't go away, but the record became more complete. By this stage, there were enough fossils being preserved to allow palaeontologists to carry out increasingly sophisticated estimates of the changes in biodiversity through time. Assisting in this analysis has been the development of large databases that track the evolutionary appearance and extinction of organisms. Palaeontologists are now able to apply statistical analyses to the record. This has allowed the rise and fall of biodiversity over the past 550 million years or so to be estimated in some detail.

The results of these analyses confirmed the presence of mass extinctions – sharp drops in biodiversity, often followed by almost equally rapid rises. The first real attempt to document these events in the 1980s suggested that there had been five such events over the past 500 million years – now forever popularised as the 'Big Five'. The largest of these occurred at the end of the geological period called the Permian (about 250 million years ago). The end-Permian mass extinction resulted in the loss of up to 96% of marine species (with correspondingly high levels of extinctions on the land). But the most famous of the Big Five is undoubtedly the mass extinction that occurred at the end of the Cretaceous period some 66 million years ago. It had a lower kill rate; current estimates of species that went extinct range between 65% and 75%. But it included the charismatic dinosaurs, ensuring its position as the most famous mass extinction of all time.

A mass extinction is defined as a rapid increase in the rate of extinction that occurs on a global scale and involves more than one animal group. Although recovery from these events can be slow, the actual extinctions are always very rapid, with some of the biggest thought to occur over an interval as short as 20 thousand years. Using this definition, one estimate suggests that there have been up to nineteen mass extinctions over the past 550 million years. Although none exceed the 96% kill rate of the end-Permian event, some now seem to be bigger than the other four members of the Big Five group.

Exactly what causes a mass extinction is a fraught subject. Over the years there have been many suggestions; some sensible, others just plain impossible. What we can say is that most mass extinctions of the past 500 million years occurred at exactly the same time as huge volcanic events. These ancient volcanic eruptions resulted in an outpouring of lava on a continental scale and the injection of incredible amounts of carbon dioxide (and other noxious gases) into the atmosphere. Carbon dioxide is a greenhouse gas, and as its level in the atmosphere rises, so do global temperatures. The amount of carbon dioxide released during these events was so large that the temperature rose to a point where the oceans themselves became significantly warmer. A warm ocean cannot carry as much oxygen as a cool one, and this results in widespread anoxia (very low levels of oxygen). As if that wasn't enough environmental stress, the high levels of atmospheric carbon dioxide also caused the acidification of the oceans. Between the acidic, oxygen-poor ocean and spiralling global temperatures, it's safe to say that the global environment would be severely stressed, undoubtedly leading to some extinctions.

In some cases, this highly stressed environment may not have been enough to cause a mass extinction; something else was needed to push the ecosystem over the edge. There are a variety of suggestions for what could provide that final push. In the case of the end-Permian event, the arrangement of the continents appears to have amplified the climatic effects. For the end-Cretaceous mass extinction, the impact of a meteorite some 10 kilometres in diameter delivered the *coup de grâce*.

So, what follows an event that has resulted in the death of up to 96% of life on Earth? There are many images in the literature that attempt to illustrate the devastation caused by this mass extinction. One image shows a few fish swimming over an almost empty sea floor where once coral reefs flourished. In another, rare reptilian survivors stagger across a broken landscape of rotting vegetation that was once a forest. As overly dramatic as these pictures sound, they are probably not far from the truth. But no matter how bad the devastation resulting from a mass extinction, life always bounced back. However horrendous we think a mass extinction is, as far as the history of life is concerned, it is just a temporary setback.

But that's life in the broadest sense. When examined in detail, it is clear that a mass extinction can completely change the make-up of the planet's biota. Basically, the assemblage of organisms that evolves after a mass extinction is never the same as the one that was decimated by it. Each mass extinction results in a wholesale clearing of ecological niches. Following the extinction event, these empty niches are available to be filled through the evolution of new, unrelated species. However, we can't pick winners; there is no way to decide before a mass extinction which species will be killed off and which will survive and diversify.

There is one mass extinction event that deserves to be singled out. It may not be as large as the other events we regard as mass extinctions, and it didn't involve dinosaurs, but it was significant. What makes this event so special is that humans are implicated in causing it. Prior to 50 thousand years ago, giants roamed the world. In Australia, kangaroos 3 metres tall lived alongside 7-metre-long monitor lizards and wombats the size of hippos. North America was inhabited by elephant-like mastodons and mammoths, which were preyed on by sabre-tooth cats and dire wolves.[2] Rhinos, cave bears, and giant Irish elks roamed Europe. Fifty thousand years ago, these animals, collectively known as a megafauna, started to die out. By 11 thousand years ago, most of these giant mammals were extinct.

[2] Yes, there really were dire wolves.

The cause of the megafaunal extinctions is still under intense discussion. Climate change certainly played a part. Over the past 50 thousand years, the Earth's climate has shifted dramatically. For most of that time, the planet was in the grip of an ice age, with glacial ice covering a great part of the globe, reaching a maximum extent about 20 thousand years ago. Following the last glacial maximum, climate generally warmed. However, superimposed on this warming trend were some significant fluctuations as the planet's climate bounced wildly from periods of intense cold and intervals of warming. Climate stabilised about 11 thousand years ago, about the time that the megafaunal extinctions ended. These rapid changes in climate must have placed severe ecological pressure on the megafauna. But, on their own, the changes in climate are unlikely to have been enough to trigger the megafaunal extinction event. After all, the megafauna had survived through several previous ice ages. The extra element that finally precipitated extinctions appears to be the arrival of humans, *Homo sapiens*. The time interval we are interested in coincides with the main migration of our direct ancestors out of Africa. It seems likely that the combination of fluctuating climate and the arrival of humans triggered the biggest extinction event in 50 million years.

Some scientists have argued that the megafaunal extinction represents the beginning of the Anthropocene defaunation. And they have a point. Sedimentary rocks of the past 11 thousand years do record the increasing influence of human activity on the environment. The spread of agriculture, the domestication of animals, and the development of industry and manufacturing have all left indelible markers in the record. But the environmental damage caused by these ancient humans pales in comparison to the damage being wrought today. I think of the last 11 thousand years as the slow fuse that leads to the explosion of human activity that defines the Anthropocene.

There are aspects of today's Anthropocene defaunation that are similar to the ancient mass extinctions. Firstly, the rate of extinction has rapidly increased. One estimate suggests that the rate at which

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amphibians are going extinct today is about 100 times faster than the pre-human rate. Secondly, the extinctions are not restricted to certain areas; they are occurring on a global scale. If it is a mass extinction, it's the youngest in the history of biodiversity. This has led to it being referred to as *the Sixth Extinction*, a nod to the original Big Five. However, the percentage of extinct species recorded today is far below the 65% to 96% level of the big ancient mass extinctions. Perhaps we can take comfort in that. But what is happening now is defaunation, and this means we shouldn't restrict our attention to the extinctions. By accepting the concept of defaunation, we must expand our focus to include the many species that are undergoing huge reductions in population size, placing them under severe threat of extinction. If we don't do something to mitigate the situation, we will lose them, and then we will be facing a mass extinction right up there alongside the one that killed the dinosaurs.

Some claim that since life has survived all the ancient mass extinctions, it will survive the current crisis. In their view, we shouldn't worry about our level of extinction growing to match the past mass extinctions; we can manage our way through. On the surface this is true; life has always survived. However, this is a simplistic reading of history. It is true that following a mass extinction event, no matter how large, biodiversity has always recovered. But that's not the whole story. Mass extinctions, especially the big ones, change the composition of the biota. Indeed, it has been argued that most evolutionary innovations are the result of the burst of activity that occurs as the biota recovers following a mass extinction. This means that the make-up of the biota that goes into a mass extinction will be different from the one that comes out the other side. In our case, there is no certainty that any future biota will include humans. We could try to ensure that humans and the species we need for our survival make it through and let the rest die out. This is a horrendous idea because we need a fully functional diverse ecosystem for the Earth System to operate properly. The biosphere is an integral part of the planet's life support system. In addition, no matter how I try to imagine the mechanics of selectively saving only some species, I come to the conclusion that it couldn't be accomplished without the loss of a significant proportion of the human population and an extremely depleted biota. I'm sure there are apocalyptic science fiction novels written about this sort of scenario. Surely it is far better to do something before we get to that point.

One of the most significant differences between the Anthropocene defaunation and the ancient mass extinctions lies in its cause. In one sense, all the ancient mass extinctions are the result of a collapse of at least a large part of the global ecosystem. Setting aside the megafaunal extinction for a moment, all of the ancient mass extinctions were triggered by natural events – massive volcanic eruptions, the arrangement of continents, sea level changes, ice ages, or meteorite impacts – operating either singly or in combination. The megafaunal extinction was in all likelihood caused by a combination of climate change and the appearance of *Homo sapiens*. The Anthropocene defaunation has only one driver: the changes that humans are inflicting on the planet's ecosystem.

At the heart of this book, however, is the message that our situation is not hopeless. It's clear that, compared with the mass extinctions contained in the fossil record, we are only at the beginning of this catastrophe. We have a little time to act before we reach the level of the ancient mass extinctions. We had better use what time we have wisely.