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How the living world evolved and where it's headed now

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The growth of life on Earth over more than 4 billion years has experienced five major extinction events, each followed by a period of rapid increase in species number. When organisms first invaded the land about 480 million years ago, another explosive proliferation of species followed. Our species, *Homo sapiens*, appeared some 300 000 years ago, developed agriculture about 11 000 years ago and grew rapidly to some 7.8 billion people, who are currently consuming about 175% of the sustainable productivity available worldwide. By mid-century (2050), we will have grown to about 9.9 billion. Wealth is very unequally distributed. Meanwhile, the Earth's mean temperature has increased by 1.1°C above pre-industrial levels, and we are on track for a total increase of 2.6 to 3.9°C. We are driving species to extinction at a rate unprecedented for the past 66 million years. These changes promise to be disastrous for the maintenance of civilization. Indeed, our only hope for a sustainable future will be for us to find a way to overcome our unremitting greed at all levels and to love one another while building social justice.

This article is part of the theme issue 'Ecological complexity and the biosphere: the next 30 years'.

Over the course of the past two centuries, the human population of Earth has exploded from one billion to 7.8 billion people and will likely increase by an additional 2.1 billion over the next 30 years. The effect of this growth by mid-century, 2050, will present the most important challenge that human beings have ever faced—the last chance to redirect our activities toward the attainment of global sustainability. With our domestic animals, we have grown to constitute 95% of the entire mammalian biomass. From initially using a small fraction of the Earth's sustainable productivity, our consumption has grown to an estimated 175% of the total, so that by the end of July each year we have used up everything potentially sustainable that is available to us (www.footprintnetwork.org). We farm and graze an estimated 40% of the planet's land surface and affect in some way every other square centimetre that exists. We apparently have only a slim chance to avoid disastrous levels of climate change, having not yet found the discipline necessary to deal with that threat appropriately. Meanwhile, nations are in direct competition to capture as much of the Earth's productivity as possible, some consuming at five or more times the level that their own land area would justify and others sinking into a state of poverty and unavoidable exploitation. We will discuss these issues in more detail in the pages that follow.

We shall now consider how our world changed to become the one we inhabit now, what has happened to it along the way and what kind of a future we are forging for other living organisms and for ourselves. Our planet formed about 4.57 billion years ago, with life appearing a few hundred million years later. Some 3 billion years ago, Cyanobacteria, the first photosynthetic organisms, began to generate oxygen, a gas that gradually increased to constitute about 20% of our atmosphere today. This oxygen shielded the first organisms that ventured onto land from the mutagenic effects of solar radiation, making it possible for the first terrestrial organisms to colonize the land some 480 million years ago, in the Ordovician Period. The first land plants, insects and fungi, with vertebrate animals following, were the earliest colonists.

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The world's first mass extinction event (one with more than three quarters of existing species becoming extinct) occurred soon after, some 450–440 million years ago (Ma). Most species of organisms were still marine at that time; an estimated 86% of all species disappeared permanently over the course of a few million years. Apparently, widespread continental glaciation and the associated rapidly falling sea levels were prime factors driving their disappearance.

The second mass extinction event occurred in the Late Devonian Period, 375–360 Ma. Like its predecessor, and even though terrestrial plants and animals were quite diverse by that time, it was mostly the marine ones that went extinct, with half of the genera and more than two-thirds of the species that existed at that time disappearing.

By far the most severe extinction event the world has experienced until now was followed at the boundary between the Permian and Triassic periods, about 251 Ma. It included the only recorded mass extinction of insects, along with more than two-thirds of the species of terrestrial vertebrates and some 96% of all species of marine organisms. Perhaps as many as 95% of all species that existed earlier disappeared! Various global calamities occurred at about the same time, but it is not clear which of them triggered this major catastrophe, which permanently altered the nature of life on Earth. Entire groups of organisms that had been abundant or even dominant earlier disappeared, with others evolving rapidly and taking their place in the ecosystems that formed as life recovered.

Some 50 million years later, the Triassic–Jurassic extinction event affected both terrestrial and marine species equally, with roughly three quarters of the total living then becoming extinct. The first dinosaurs, mammals and vascular plants (including gymnosperms) had appeared earlier and survived, with dinosaurs flourishing during the following 150 million year period.

The most recent mass extinction event, the one that marked the end of the Cretaceous Period (66 Ma), resulted in the elimination of all dinosaurs that existed at that time and the start of the age of mammals, which had coexisted with the dinosaurs for tens of millions of years. Physically, the extinction experiences then almost certainly resulted from the persistent global blanket of clouds thrown up by the impact of a huge asteroid off the end of what is now the Yucatán Peninsula in Mexico. Most land plants survived, which is difficult to understand in view of the darkened conditions. In any case, they diversified and came to dominate most terrestrial habitats, along with surviving lines of reptiles, birds, mammals, insects and other groups.

During the subsequent Cenozoic Era, moderate climates gradually warmed during the first half of the era. The clear differentiation between the ecosystems of lower and higher latitudes, so familiar to us, had not yet become obvious. Starting about 30 Ma, continental glaciers began to form in the Polar Regions, accompanied by spreading aridity starting about 15 Ma at mid-latitudes. Eventually, frigid Polar climates, with their extensive taiga and tundra ecosystems, on the one hand, and hot Equatorial ones, dominated by tropical lowland rainforest, on the other, came to resemble those of today.

Into this world, our ancestors, the first hominids, split from the other African apes about 6–8 Ma, becoming part of functioning ecosystems and evolving into a number of distinct genera and species. By the time our species, *Homo sapiens*, evolved in Africa, at least 300 000 years ago, other members of our genus had reached Eurasia, but not ventured beyond it. The intercontinental migration of our species took place during a period of glacial expansion that lasted from 110 000 to about 10 000 years before present. Humans had ventured to Eurasia by 70 000 years ago, soon reaching Australia and, no more than 17 500 years ago, North America, from which they migrated over the following several thousand years to the southern reaches of South America.

It is estimated that no more than 2% of the species that have existed during the history of life on Earth still exist today. They form the ecosystems that support us today, with our dependency on biodiversity complete. Indeed, we ourselves are a part of biodiversity, a fact that we disregard only at our peril. Not only have the organisms with which we share this planet formed the ecosystems that shaped the composition of the air we breathe, the water that we need for survival, and the soil on which we grow our crops, they continue to purify the air and the water and condition the soil. Recently, we have divided the characteristics of our dependency into the major categories of ecosystem services: provisioning, such as the production of food and water; regulating, such as the control of climate and disease; supporting, such as nutrient cycles and oxygen production; and cultural, such as spiritual and recreational benefits. These services exist because of interactions between organisms within ecosystems as well as the abiotic environment. Of critical importance, no one knows the point at which the subtraction of a single species, or of a number of species, would lead to the collapse of a particular ecosystem. Certainly, breaking points do exist, a major reason that the contemporary mass extinction, discussed below, is a matter of such concern.

Once our ancestors had domesticated animals and developed crop agriculture their numbers began to grow rapidly. They were then able to remain together for long periods in a single place rather than move about continually in search for food. These advances occurred about 11 000 years ago, during a period of rising temperatures following the end of the preceding cold period. At that time, the entire population of Europe consisted of an estimated 100 000 people, and that of the world, of about one million. As our numbers grew, our impact on the planet increased with them. By about 3000 years ago, pastoralists, agriculturists and hunter–gatherers had transformed large areas as they gathered and grew food for their increasing numbers [1]. The human population grew steadily, reaching about 200 million people at the time of the Roman Empire; 500 million in 1500, as the Renaissance got underway; a billion in Napoleonic times; and a rapidly growing 7.8 billion today, increasing by about 200 000 people net per day (www.prb.org) toward an anticipated 9.9 billion 30 years from now, at mid-century.

According to the Global Footprint Network (www.footprintnetwork.org), and as mentioned above, we are currently consuming some 175% of the world's sustainable productivity. We passed 'Global Overshoot Day', the date on which we had used up all of the available sustainable productivity, by late July in 2019, and a few weeks later in 2020 because of the COVID-19 pandemic. Such a level of consumption, which we clearly cannot maintain, has also led to great inequalities between the productivity available to different nations and within nations, with seemingly endless competition for an ever-larger share of the global total.

Given such relationships, it is obvious that we are having an enormously destructive effect on the Earth's ecosystems. Their capacity to function depends on the interactions among millions of species, most of them unknown to us; no more than 20% of the world's species have yet been given names and classified. Obviously, ecosystems vary greatly from place to place, from climate to climate. We understand them through the science of ecology, which began less than a century ago, and what we have learned is still quite limited.

Clearly, we can reasonably attempt to estimate extinction rates only for those groups of organisms that are relatively well known, including vertebrate animals, plants, butterflies and a very few others. For them, we have learned that the extinction rates have climbed in some cases to about 1000 times what they have been historically, and that they are still climbing rapidly [2,3]. For some groups of organisms, we can determine how many of the species are so rare or limited in distribution that they are in danger of complete elimination now. About a fifth of all species appear to fall into this category and are thus likely to become extinct over the next few decades, with as many as twice that number by the end of this century. Consequently, the evidence is strong that we have entered the sixth mass extinction event already [4–6]. To limit the losses that will be associated with it, we must act immediately and forcefully.

Clearly, the spread of agriculture and other forms of land use constitute the main driving force behind these losses. Over Eurasia, land clearing would have proceeded steadily but relatively slowly from 11 000 years BP to 1500 AD [7]. Although there was some earlier land clearing in Australia and the Americas before Europeans arrived there, it certainly expanded greatly during the past 500 years—primarily for agriculture. In 1500 AD, at the beginning of the Renaissance, the global population was about 500 million people, with extensive agriculture developed in Europe and the Near East and in East Asia. It took three centuries for the number of people to double, a growth spurred on by the Industrial Revolution, which started around 1760 and ran at full speed until 1820 or 1840. As larger, industrialized cities were established and growing numbers of people crowded into them, fewer and fewer farmers practiced agriculture, but they did so on a larger and more intensive scale than previously. After World War II, a century began in which our global population is in the course of quadrupling to some 10 billion people—by far the most rapid period of growth that *Homo sapiens* has ever experienced.

Some nations, including the United States, Canada and Argentina, have the internal capacity to produce their own food and a great deal more for export, even though they import many other commodities from outside their boundaries. Others do not have such a capacity. Some, including the poorer nations of Africa, intensively exploited by rich nations, are sinking into an environmental poverty trap [8]. The nations of Western Europe are rich and can afford to import whatever they need and use any agricultural methods that they select. In this connection, Europe has largely been opposed to the adoption of all new methods developed for agriculture despite their proven safety. Unfortunately, European short-sightedness has deprived many hungry regions of the world of these foods and thus helped to facilitate widespread starvation and illness. To build a sustainable planet will require the explicit recognition that we inhabit only one Earth, with all nations and all people necessarily collaborators in preserving it from disaster as our numbers and rates of consumption continue to grow.

Worldwide, about 11% of the Earth's land area is devoted to crops, with about 30% more used, mostly unsustainably, for grazing. An excellent recent review [9] discusses the trade-off that we face between the food needs of our rapidly growing population and biodiversity. Clearly, the prospects are daunting, with 2.2 billion additional people projected in the global total over the next 30 years, and many people starving or lacking essential nutrients even now.

Agriculture is also spreading extensively in the tropics, where at least two-thirds of all species, the great majority of them unknown, exist. If we want to preserve much of biodiversity, the rich nations of the world will need much more actively to recognize the needs of the poor so that all will have the capacity to devote resources to conservation. So far, I consider largely because of this inequity, our efforts have been relatively ineffective. For example, since the ratification of the Convention on Biological Diversity in 1992, more than a quarter of the tropical forests that were standing then have been cut, clearly accompanied by major losses in biodiversity. Few predict that any substantial stands of tropical forest will remain by the end of the present century. Why? Well, over the next 70 years, experts have calculated that the population of Sub-Saharan Africa, currently 1.1 billion people, with a current GNP *per capita* of about $4000, will quadruple to about 4.4 billion (prb.org/worldpopdata). Relationships of this kind seriously challenge those who speak about a 'fertility dividend', as if natural productivity would expand naturally to meet the needs of the people, in some kind of imagined economy that simply does not work. For Indo-Malaysia, the future seems equally bleak (e.g. [10]). Growing numbers of people lead inevitably to more clearing for agriculture and direct uses of the forest for other purposes; the inevitable result is that local biodiversity shrinks rapidly both qualitatively and quantitatively. Janzen & Hallwachs [11] impressively describe the accompanying decline in tropical insects, which has clearly reached runaway proportions.

A second major factor, and one that is rapidly growing in importance, is global climate change, which has resulted in large measure from our burning enormous amounts of coal, oil and natural gas and thus changing the characteristics of the Earth's atmosphere so that it traps increasing amounts of heat. The Earth's mean temperature has increased by 1.1°C over pre-industrial levels. Recently, the World Climate Research Programme estimated that we are on track for an increase of 2.6 to 3.9°C, even ruling out some of the worst-case scenarios. We have reached a carbon dioxide level in the atmosphere of 420 ppm, which is half-way to the concentration estimated to drive the levels just mentioned by 2060, which would be a complete disaster for biodiversity [12] and indeed for many aspects of the civilization that we have built. Indeed, unless we are willing and able to take concrete steps to limit our damaging activities, the increase above background is estimated to have climbed by 1.5°C—supposed to be the point of no return—within a decade (i.e. by 2030; [13])—and keep climbing [14]. As current cultivated areas, where large amounts of biodiversity have already been lost, are moved to new areas that assume their original climate, large additional amounts of biodiversity will certainly be lost [15]. Certainly global warming promises to surpass habitat destruction as a

factor in biological extinction in the very near future unless we act immediately.

What should we attempt to do in the face of these compounded problems (e.g. [16])? Few people who have thought seriously about the matter have concluded that the Earth can remain a stable home for more than 2–3 billion people indefinitely; population growth has been the greatest challenge for all natural systems. We must undertake the empowerment of women and children, more than 1 billion of whose rights we collectively deny. In rich countries like the U.S.A. and those of Western Europe, we must strive to nourish an international outlook so that for reasons of morality or love we begin to care enough about the people who live in the other nations of Earth to try to do something to help them. Social justice is not an option, but rather a necessity, if we wish to forge a sustainable future for our children and grandchildren. The cooperative preservation of as much biodiversity as possible is an unavoidable responsibility if we truly care about that future.

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