2 HUMANKIND AND THE PLANET

According to scientists, Earth is a single, integrated system at the planetary level. It has existed for about 4.6 billion years and has coevolved with life for the vast majority of that time. Over this long existence, the Earth system has been through all kinds of shocks – internal and external – and embarked on numerous transitions and evolutionary pathways.

Our species *Homo sapiens* arrived relatively recently in the Earth system. Scientists believe that modern humans emerged in Africa sometime between 100,000 and 150,000 years ago and quickly spread around the globe.

However, humans have only really flourished in the last 12,000 years, during the relatively stable environmental and climatic period called the *Holocene*. This geological era began with the last major glacial epoch, or Ice Age. Since then, there have been smaller climatic shifts – notably the "Little Ice Age" between about 1200 and 1700 AD. But generally, the Holocene has been relatively warm and environmentally benign. It has enabled major terrestrial, freshwater and marine ecosystems to evolve and stabilize. Most notably, it has allowed humans to multiply, prosper and become the dominant species on our planet.

As we noted in Chapter 1, human activity is now on the verge of altering irrevocably the functioning of the Earth system. Since the mid-twentieth-century "Great Acceleration" of population growth, industrialization and mineral and energy use, we have impacted the biosphere so significantly that scientists believe that humans have created a new geological age – the *Anthropocene*.[1]

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The fundamental challenge of the Anthropocene is how much humans can continue to modify the structure and functioning of the Earth system and still keep it sufficiently stable to support human life as we know it. As the global environmental risks caused by our activities mount, there is a real danger of inflicting significant and long-lasting changes to the entire Earth system. Crossing this "tipping point" is likely to be very harmful for humans, ecosystems and life itself. The Earth system will survive, but the favorable conditions of the Holocene may not. There will be rapid and substantial changes to the global climate and environment that will make it hostile to human habitation. It is in this sense that our planet has become "fragile." We risk transforming an Earth system with favorable climatic and environmental conditions into an unknown and alien world in which humans may struggle to exist.

However, the Earth did not become stressed and less resilient overnight. The increased "fragility" of the Holocene state of the Earth system and the rise in four critical threats to the global environment – climate change, land use and biodiversity loss, freshwater scarcity and deteriorating marine and coastal habitats – is the culmination of a long process of human impacts on the Earth system over the past 10,000 years. The purpose of this chapter is to briefly overview this process, highlighting the key historical eras when our relationship with nature changed irrevocably. I focus on five eras: the rise of agriculture 10,000 years ago and up to around 1000 AD; the emergence of global trade and the world economy (1000–1500 AD); the period of Global Frontiers (1500–1750); the fossil fuel age (1750–1970); and the Great Acceleration (1970–present). We conclude by reviewing the mounting scientific evidence that the last era has led to growing environmental risks and the existential threat of transcending planetary boundaries.

Early Human Impacts on the Earth System

Much of the current predicament of our planet has arisen through the long history of how humans have exploited *nature* to create *wealth*.[2]

This process has evolved and accelerated dramatically in recent eras, yet for most of our existence, humans have had little impact on the surrounding environment. Until 10,000 years ago or so, all humans lived as hunter-gatherers and had little interest in accumulating material

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possessions, land or natural resources. In these societies, mobility and adaptability to nature were the key social traits that guaranteed economic survival of individuals and their communities. Material wealth as we know it today was a meaningless concept for early humans. Humans were few in number and scarce. In contrast, natural wealth was everywhere and plentiful. Finding new hunting and foraging grounds was relatively easy, and the raw materials for clothing and other essential items for survival were readily available in the wild. There was no need to hoard, possess or protect natural assets.[3]

The first major change in humans' relationship with nature was the rise of agriculture. Around 10,000 years ago, farmers and herders supplanted hunter-gatherers, and *wealth creation* began in earnest. Sedentary agricultural activities tied humans to specific locations, fertile land, forests for timber; mines and other natural resources became valuable sources of production; food and other commodities were produced in surplus and traded; and human settlements grew and expanded into nations and empires. For a few thousand years this process began tentatively, with experimentation in crop planting by sedentary hunter-gatherers in different parts of the world. By 5000 BC much of the global population lived by farming, and by 3000 BC the first agricultural-based "empire states" emerged.[4]

Once agriculture became the dominant economic activity, humans associated affluence with the accumulation of fertile land and key natural resources, such as wood, water, building stone, precious stones and gems and metals. Labor was important but less so than livestock for food, transport, work and even warfare. In other words, basic natural resource assets – or *natural capital* – were the main sources of economic wealth for both individuals and human societies. One consequence was that human societies also became less egalitarian, as sharing and cooperation gave way to accumulation of individual wealth and affluence. Creation of such surpluses led to dominance by elites, social status and stratification.[5]

Amassing this natural wealth fostered the evolution of permanent agricultural settlements of large villages and towns into more complex and populated urban centers and political states – the emergence of cities and empires. This occurred in a number of regions across the world from 3000 BC to 1000 AD. Although dependent on surrounding agricultural land for food surpluses, the urban centers that controlled these great empires and early civilizations also required a variety of

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natural resources to sustain their economic wealth and power, and to provide security in times of drought, plague, war and other calamities. Imperial expansion and urban growth required securing new supplies of fertile land, natural resources and raw materials.

As early civilizations grew and their populations and empires expanded, their drive to obtain and exploit more natural wealth placed increasing stress on the surrounding environment. It also caused social conflicts and warfare between states. Many major city-states and empires suffered from serious problems of natural resource depletion and environmental degradation (see Table 2.1). The resulting ecological catastrophe may have been a factor in the civilization's eventual collapse.[6]

Although significant human-induced environmental degradation at the local and regional levels did occur through expansion of early civilizations and empire, the global impact was negligible. This continued throughout early history as human populations and their economic activity expanded still further.

The second major shift in humankind's relationship with the biosphere took place between 1000 and 1500 AD with the emergence of global trade. Trade was always important to agricultural-based societies as they sought more natural wealth to exploit and consume. Just as the emerging city-states and civilizations of 3000 BC–1000 AD could not exist without an agricultural base producing large food surpluses for their urban-based populations, they also became dependent on securing raw materials from trade with nearby resource-abundant regions.

So successful was trade in helping nations accumulate wealth that the expansion of local and regional trade networks continued across the globe. Trade sometimes supplanted, and other times aided, the appropriation of fertile land and other natural resources through conflict, conquest and colonization. The result was that regional trade networks continued to grow and merge. These networks coalesced into a nascent "world economy" by 1000 AD, and from 1000 to 1500, the upsurge in trade between countries and regions ushered in an unprecedented era of global population and economic growth. By 1500, an international economy was firmly established. Over this 500-year period, world population nearly doubled, and the value of global production per person increased from $436 to $566.[7]

Trade fostered wealth creation. That is, trade facilitated access to the most important sources of "wealth" across the world. Economies

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Table 2.1. Civilizations and environmental degradation, 3000 BC–1000 AD

Civilization	Period	Human-Induced Environmental Degradation
Sumer, Southern Mesopotamia	2200–1700 BC	Soil salinity; land degradation; deforestation; river and canal silting
Egypt, Nile Valley[a]	2200–1700 BC	Deforestation; land degradation; soil salinity; wildlife extinction
Harappa, Indus Valley	1800–1500 BC	Land degradation; overgrazing; salinity; deforestation; flooding
Crete	ca. 1500 BC	Deforestation; soil erosion
Mycenaean Greece	1200–1000 BC	Deforestation; soil erosion; overgrazing
Assyrian Empire[b]	1000–600 BC	Deforestation
Greek city-states	ca. 500–200 BC	Deforestation; soil erosion; river silting; flooding; pollution
Chin and Han dynasties, China[c]	221 BC–220 AD	Deforestation; flooding; erosion; river silting; wildlife extinction
Roman Empire	200–500 AD	Land degradation; deforestation; soil erosion; river siltation; air and water pollution; lead poisoning; wildlife extinction
Satingpra Empire, Thailand[d]	500–850 AD	Deforestation; land degradation
Various dynasties, China[e]	600–1000 AD	Deforestation; flooding; erosion; river silting
Various empires, Japan	600–850 AD	Deforestation; flooding; erosion; river silting
Maya, Central America[f]	830–930 AD	Land degradation; erosion; deforestation; river silting; weed incursion;
Srivijaya, Sumatra	ca. 1000 AD	Deforestation

Notes: Period refers to either the approximate period of decline of the civilization and/or when evidence of extensive human-induced environmental damage is cited.
[a] From Chew (2006); Hughes (2001); and Issar and Zohar (2004).
[b] From Parker (2002).
[c] See also Elvin (1993) and Hughes (2001).
[d] From Stargart (1998).
[e] See also Elvin (1993) and McNeill (1998).
[f] From Culbert (1988), Hughes (2001); and Johnson (2003).
Source: From Chew (2001) unless otherwise indicated.

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were still overwhelmingly agrarian. This meant that the main sources of wealth had not changed since the emergence of agricultural-based empires starting around 3000 BC. Economic wealth was still principally defined by the three most important assets of agricultural societies: fertile land, natural resources and raw materials. Precious gems and metals were status symbols of wealth but were growing in importance as "stores" of value and as "mediums of exchange" to pay for items of trade. The most important forms of reproducible capital were dwellings, basic tools and utensils, livestock and labor, especially in the form of slaves.

Figure 2.1 characterizes the major regions involved in the emerging world trade system around 1200–1300. This figure indicates how differences in natural resource endowments and ecological conditions influenced the specialization and trade in different natural resource-based products by region. This was not yet a truly global economy, as it excluded the American and Australian continents, as well as large parts of sub-Saharan Africa and much of the Pacific. However, the largest economies in the world, which contained most of the world's population, were connected by this extensive trading network.

The long-distance trade networks in raw materials, precious metals, spices and other commodities represented in Figure 2.1 may not have caused significant global ecological impacts. Yet the nascent world economy laid the foundation for such impacts to begin emerging from 1500 onward. First, the growth in trade fostered not only the exchange of goods but also the rapid transmission of people, ideas, technologies, religions and, unfortunately, pathogens.[8] Second, trade encouraged people to find new sources of natural resources to exploit. This meant that economies became even more dependent on "opening up" new frontiers of land and natural resources to such exploitation. Third, wealth accumulation through trade also created both the means and the opportunities for more powerful states and empires to appropriate land and natural resources through conquest and colonization of neighboring and distant territories. Finally, trade encouraged a new type of economy to emerge – market- and commercially oriented and based on long-distance trade – essentially the hallmark of Western European economies.

For several centuries, the wealth and power of Western European states grew as a result of long-distance trade and exploitation of new frontiers of land and natural resources within Europe and neighboring regions. It was a logical extension of this strategy to expand

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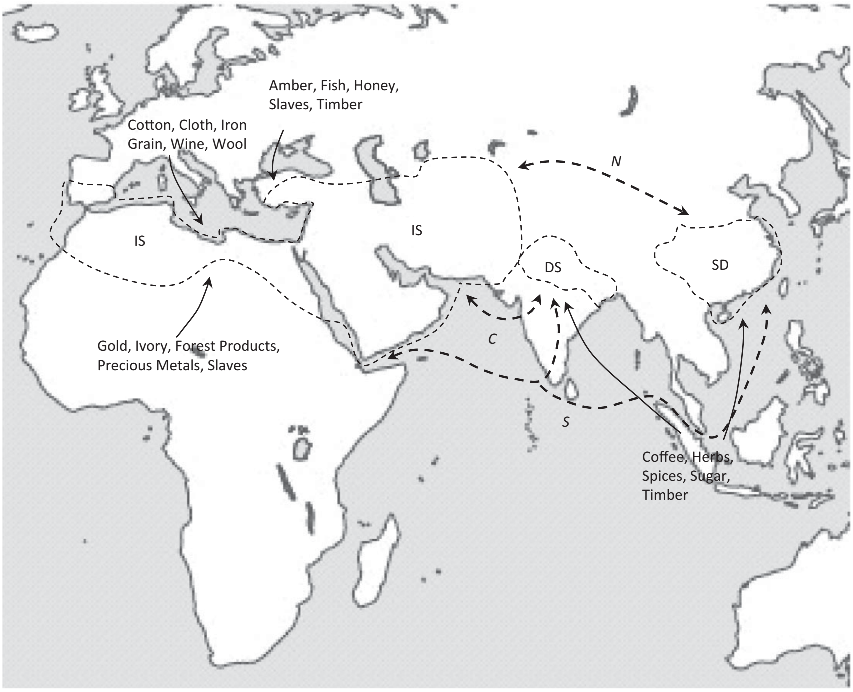

Figure 2.1 The emerging world economy, ca. 1200–1300 AD
Notes: IS = Islamic states of North Africa, Middle East and West Asia (e.g., Abbasids, Almohads, Arabs, Ayyubids, Ghurids, Kwaresmians, Ortoquids, Salgharids, Seljuks and Zengids, ca. 1200).
DS = Delhi Sultanates (Mamluk Dynasty, 1206–1290).
SD = Sung Dynasty (during Southern Sung, 1127–1279).
N = Northern east–west trade route.
C = Central east–west trade route.
S = Southern east–west trade route.
Source: Barbier (2011), figure 4.1.

their dominance of trade and natural resources to the global level. By the twelfth and thirteenth centuries, Western Europe specialized in select natural resource products, including some processed products, and key services such as commerce and maritime transport. It was no longer "underdeveloped" but more of a "semi-developed" or "middle-income" region. By 1500, Western Europe had the highest per capita GDP levels in the world, and the largest share of global GDP after China and India.[9]

The period from 1500 to 1750 represented another important shift in humankind's exploitation of the Earth, and it became known as

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the era of Global Frontiers. During this age, economic development was further spurred by finding and exploiting new frontiers of land and other natural resources. International commerce facilitated the growth of many important markets and trading routes for a variety of resource commodities, which in turn were fostered by the discovery and exploitation of new sources of land and natural resources across the world. From 1500 onward, the expansion of global trade and frontiers was self-reinforcing.

By 1500, the key indicator of any state's economic wealth, political influence and military might was its ability to accrue gold, silver and other precious metals. By the seventeenth and eighteenth centuries, a handful of European states had leveraged their dominance of key sea routes into powerful "ocean empires" that controlled the lucrative global trade in key natural resource products (see Table 2.2). This trade and commercial strategy allowed the small European maritime states to accumulate the reserves of gold and silver necessary to become global economic and military powers.

The need to accumulate trade surpluses at the expense of their competitors provided the motivation for European states to embark on global frontier expansion. This in turn spurred the exploitation of new sources of natural resources and provided the justification for the promotion of trade and mercantilist policies. Through its unrelenting exploitation of the Global Frontiers from 1500 onward, Western Europe obtained a vast array of natural wealth, land frontiers for settlement, as well as fishing, plantation, mining and other resource frontiers. These frontiers not only provided an outlet for poor populations emigrating from Europe and other regions in search of better economic opportunities but also created large resource windfalls to the benefit of European economies.

For the first time in human history, exploitation of the environment occurred on a global scale for economic development and enhancing human welfare. As the economic historian Eric Jones notes, Europe had four main "Extra-European resources" that "were vast, varied, and cheap": ocean fisheries, including for whale and seal; the boreal woods of Northern Europe; land in the tropics and subtropics for growing sugar, tobacco, cotton, indigo and rice; and land in temperate North and South America, South Africa, Australia and the steppes of southern Russia for growing grain.[10] European states controlled these global land and resource frontiers first through trade, discovery and exploration,

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Table 2.2. Ocean empires and natural resource trade, seventeenth and eighteenth centuries

Regions	Main Products	European States
East Indies (Malaysian peninsula; Indonesian archipelago)	Spices, pepper, medicinal herbs, dyestuffs, woods, sugar	Portugal, the Netherlands, France, England
India (Cambay, Malabar and Coromandel coasts; Bengal; Ceylon)	Textiles, metalwork, silk, pepper, spices, indigo, saltpeter	Portugal, the Netherlands, France, England, Denmark
China	porcelain, silk, tea	Portugal, the Netherlands, France, England
Guinea (west coast of Africa from Cape Verde to Cape Lopez)	Slaves, gold, ivory, feathers	Portugal, the Netherlands, France, England, Denmark, Sweden, Spain, Brandenburg States
West Indies (Caribbean islands)	Sugar, tobacco, cotton, rice, dyestuffs	Spain, the Netherlands, France, England, Denmark, Sweden
South America (e.g. Mexico, Guyana and Brazil)	Sugar, silver, tobacco, cotton, rice, dyestuffs	Spain, the Netherlands, Portugal
North America (e.g. Canada and thirteen American colonies)	fish, fur, timber, cotton, tobacco, rice	England, France, Spain, the Netherlands, Russia, Denmark, Sweden

Source: Barbier (2011), table 5.3.

followed by conquest and colonization of territory. As the historian Alfred Crosby suggests, this "biological expansion" of Western European states across the globe can be characterized as a process of "ecological imperialism," in which new lands, natural resources and peoples were conquered, subjugated and exploited.[11]

Global migration changed significantly after 1500. Before the sixteenth century, when people migrated to settle new lands or exploit abundant natural resources, they were restricted to moving to nearby uninhabited areas, such as previously untouched forests, wetlands, grassland and hills, or to adjacent territories and borderlands.

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As shipping technologies and long-distance sea transport improved and became less costly, from the sixteenth century onward migration became more global. For the first time in world history, transoceanic settlement and exploitation of new lands occurred. For example, between 1500 and 1760, nearly 6 million people immigrated to the "New World" colonies of North and South America. Notably, of these more than 60 percent were Africans shipped involuntarily as slaves. As a result, over this period the ratio of slave to European immigrants to the American colonies was 2 to 1.[12]

The colonization strategy for Global Frontiers was driven by the desire to seek and accumulate wealth from "unclaimed" regions, and to do this before others could acquire and appropriate them. The manner in which land and natural resources were exploited was influenced by geography, climate, disease and other environmental factors that determined "whether European colonists could safely settle in a particular location."[13] In environments that were less conducive to settlement and caused high mortality among settlers (e.g. tropical diseases such as malaria and yellow fever), the formation of extractive states and the use of slavery to exploit natural resources was more likely. "In fact, the main purpose of the extractive state was to transfer as much of the resources of the colony to the colonizer."[14] These extractive states tended to prevail in the tropical regions of Latin America and the Caribbean, Asia and sub-Saharan Africa. However, in environments more favorable to settlement, such as Canada, the United States, Australia, New Zealand and temperate South America, the creation of "neo-Europes" occurred.[15] In these temperate regions, Europeans settled in large numbers and the colonial settlers tried to replicate European institutions with strong emphasis on private property and market incentives to spur commercial activities and checks against government power.

The global exploitation of land and natural resources from 1500 to 1750 was not just a European phenomenon. It occurred on an extensive scale across the world, especially in the agricultural-based empires of China, India, Russia and the Middle East.[16] For example, the Mughal Empire (1526–1707) in India depended on aggressive expansion of its agricultural land base.[17] By 1690, the Mughal Empire's territory comprised 3.2 million km^2 and around 100 million people – nearly the entire Indian subcontinent except for its southern tip. The Mughal Empire promoted frontier settlement and cultivation of new lands, starting with the rest of the River Ganges plain in the mid-sixteenth century and then across the Bengal Delta (now modern-day Bangladesh). This was accomplished in three steps. First, through conquest and pacification in the eastern delta. Second, forest clearing, conversion of wetlands to rice paddies and pioneer settlement that greatly increased agricultural production. Finally, urbanization and industrialization in the form of export-oriented silk and cotton textiles. Such frontier expansion and development continued under British conquest and colonial rule well into the nineteenth and twentieth centuries.

In sum, by 1750 humankind's impact on Planet Earth had reached a global scale. No longer was human-induced environmental degradation, resource exploitation and land conversion confined to local or regional impacts. Global domination of nature and surrounding environments had become the norm for early modern economies, and was synonymous with continued economic progress, wealth creation and social power. Although humankind had yet developed the technical means or sources of energy that could inflict irreversible damage on major biomes or the entire biosphere, the trend of exploiting the environment for sources of raw materials, new land and energy, or as a sink for waste and pollution, had been set for all economies. This soon paved the way for exponentially growing economic pressures on the natural environment during the nineteenth and twentieth centuries, which has continued up to the present day. In other words, by 1750, the world economy was poised to inflict massive destruction of nature on a global scale – it only lacked the means to do so. The environmental consequences of this economic exploitation of "unending frontiers" has been summarized succinctly by the environmental historian John Richards:

> The early modern near-doubling of human numbers generated new pressures on the natural world . . . shared long-term historical processes – settlement frontiers, biological invasions, and the world hunt – imposed shattering changes on regional ecosystems around the world. During the early modern period, there was an irresistible, and seemingly irreversible trend towards more intensive human control and use of the land and the natural environment. As this occurred, those intricate local assemblages of vegetation and fauna that had long flourished with far less human intervention lost complexity, lost diversity, lost numerous species, and sometimes were even

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eradicated completely . . . These processes once underway, have continued with little restraint or diversion in the nineteenth and twentieth centuries.[18]

The Fossil Fuel Age

From 1750 onward, with the onset of the Industrial Revolution, the global balance between humankind and nature changed dramatically. As the historian Arnold Toynbee noted, "By making the Industrial Revolution, Man exposed the biosphere, including Man himself, to a threat that had no precedent."[19]

Much has been written about the causes and consequences of the Industrial Revolution. Here, we focus on its most important consequence for humankind's relationship with the planet: *the rise of the global fossil fuel age*.

Up until the mid-eighteenth century, the economic wealth of Western Europe and the other great economic powers in Asia and the Near East was roughly equal. This wealth was largely associated with accumulation of agricultural land, livestock, gold, silver and other precious metals and gems, and in many places, the "ownership" of human labor (slaves, serfs or indentured servants). The Industrial Revolution, which started in Western Europe and quickly spread across the globe, irrevocably altered both the process of creating wealth and its composition. It did so through a massive shift in the innovation, productivity and structure of economies. Industrialization in Europe transformed an "advanced organic economy" dependent on land and traditional energy sources, such as water, wind, biomass, animal and human power, to a mineral-based economy, capable of achieving unparalleled levels of sustained growth in manufactures and agriculture through exploiting the new and relatively abundant fossil fuel energy resources.[20]

However, these changes did not happen all at once in the mid-eighteenth century, but took centuries to unfold. They centered on key innovations, which were in turn the culmination of decades of scientific and knowledge advances in Western economies. These advances were, in turn, directly related to the vast accumulation of wealth created through global domination of nature and surrounding environments. This wealth allowed Western states to invest in the creation of new

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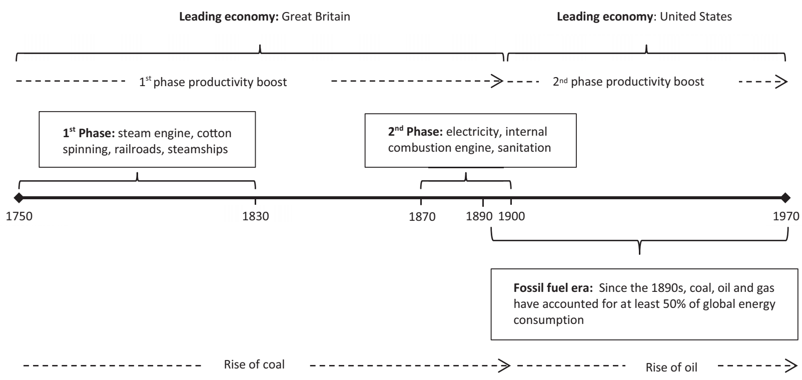

Figure 2.2 Key timelines of the Industrial Revolution, 1750–1970
Notes: The first phase of key innovations of the Industrial Revolution occurred between 1750 and 1830, and centered on steam power and coal. They led to the global economic dominance of Great Britain and boosted the productivity of all industrializing nations that followed Britain's example until 1900. The second phase of innovations of the Industrial Revolution were between 1870 and 1900, and were based largely on electricity and the internal combustion engine – made possible by the new hydrocarbons oil and gas. These innovations led to the economic rise of the United States, which became the model for twentieth-century industrialization and boosted global productivity until 1970.
Source: Barbier (2015), figure 2.2

scientific ideas, processes and applications that unleashed the energy potential of a new and abundant resource – fossil fuels – that ultimately transformed their economies and societies.

As Figure 2.2 indicates, this process comprised two distinct "phases" of key innovations and fossil fuel use starting in 1750, which caused significant impacts on global economic development and productivity for many decades after the initial inventions were introduced. Figure 2.2 depicts the timelines associated with the key innovations linked to these two distinct phases of the Industrial Revolution.[21]

The first phase of the Industrial Revolution occurred between 1750 and 1830. This centered on key inventions, such as the steam engine, cotton spinning, railroads and steamships (see Figure 2.2). These innovations helped propel Great Britain to global economic and political dominance, and they had lasting impacts on all industrializing economies up until 1900. The second phase of the Industrial Revolution centered on key innovations between 1870 and1900, such as electricity, the internal combustion engine, water and sanitation systems, refrigerated transport and oil

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and gas refining. These innovations spurred considerable industrial, transport and urban developments that boosted productivity until 1970, and led to the economic rise and worldwide dominance of the United States.

As indicated in Figure 2.2, by the late nineteenth century, the spread of industrialization across the globe had ushered in fully the fossil fuel age. As suggested by the scientist Vaclav Smil, this era started as "sometime during the 1890s when of crude oil, and a small amount of natural gas began supplying more than half of the world's total primary energy needs."[22] This new era of fossil fuel energy quickly led to two important global trends. First, world energy consumption began growing exponentially. Second, the composition of energy consumption changed dramatically throughout the two phases of the Industrial Revolution.

By 1900, global energy consumption had doubled from what it was in 1800. By 1970, consumption was five times greater still. In 1800, biomass energy sources – fuelwood, charcoal and crop residues – comprised 80 percent of world energy consumption. However, the nineteenth-century industrialization of major economies led to the rapid spread of coal consumption and the replacement of charcoal for indoor heating and metal production by coal, coke and gas. By 1900, fossil fuels had surpassed biomass in global energy consumption. In the early twentieth century, gas and oil use, for heating, electricity generation and transportation, began their meteoric rise, with oil supplanting coal as the dominant fuel by the early 1960s. By the 1970s, more than 90 percent of global energy consumption consisted of fossil fuels.[23]

The dawn of the fossil fuel age also meant that this resource displaced fertile land as the dominant source of natural wealth required by economies. Innovations ensured that fossil fuels were cheaper to discover, extract and develop, and improvements in transportation reduced the costs of shipping these bulky resources within and between countries. Fossil fuel use became associated with wealth accumulation of all economies, but the expansion of trade and transport networks reduced the costs of exploiting new and abundant sources and shipping them to any economy in the world. As the fossil fuel age progressed, fossil fuels became a global commodity traded on international markets, and economies could industrialize and grow richer without necessarily having their own domestic sources of cheap and accessible fossil fuels.

Inexpensive and abundant supplies of fossil fuels profoundly changed the structure of economies, transforming agriculture and transportation while creating new industries and modes of production. Fossil fuel consumption, industrialization and economic development was instrumental for the vast improvement in material living standards, life expectancy and quality of life for humans during this era. In 1700, around 500 million people lived on the planet; by 1970 the global population had reached 4 billion. Over this period, real gross domestic product (GDP) per person more than quadrupled. In 1700, average real GDP per capita in the world was around $1,400, and by 1970 it was over $6,200.[24]

The fossil fuel era and the industrialization of economies brought other critical transformations as well. There was a dramatic change not only in our use of energy, but also land, water and raw materials. The expansion in energy and raw material use also created more land, air and water pollution and inorganic and toxic wastes.

In agriculture, cheap fossil fuel energy made other inputs, notably fertilizer, machines and even irrigation water, inexpensive substitutes for traditional productive assets such as land, draught animals and labor. Agricultural productivity, in terms of both output per land and labor used, increased significantly. Falling transportation costs and the expanding road and rail networks facilitated the rapid transport of farming inputs and outputs across countries. Dramatic improvements in shipping, and then air transport, spurred falling international costs of transporting agricultural commodities, raw materials, minerals and fossil fuels. The globalization of commodity markets and trade enabled all economies to have better and cheaper access to a wider type and quantity of natural resources compared to their own sovereign endowments. As a result of global trade, all economies, and especially high-income countries such as the United States, Western Europe, Japan and others, could sustain their economic expansion through consuming energy, mineral and raw material products well in excess of their natural endowments of these commodities.

By the twentieth century, rapid industrialization was facilitated by the exponential growth in fossil fuel energy use, largely attributable to three "prime movers" that radically altered productive capacities and industrial energy efficiency in the economy: electricity generation, the internal combustion engine and the development of the petroleum-based chemical industry. The lead economy in this global development was the United States (see Figure 2.2). As other countries have continued to follow this "US model" of development ever since, it is highly instructive to explore how this structural transformation first occurred in the United States during the twentieth century.

For example, the first three decades of the twentieth century saw a remarkable transition in the United States from firm-generated steam power to electrical energy purchased from central power stations. Centralization of electricity generation and expansion of the grid network led, in turn, to an exponential growth in energy use by US firms and households in less than three decades. In 1910, 25 percent of factories used electric power, but by 1930, 75 percent of factories used electricity; similarly, the use of electric lighting by urban households increased from 33 percent in1909 to 96 percent by 1939.[25]

The abundant US supplies of petroleum fostered the development of the internal combustion engine, the automobile and the use of roads. As with electrification, the automobile and a national road network helped transform the entire US economy.[26] The emergence of the petroleum industry in the United States in the 1920s and 1930s also led to the rise of the economically important petro-chemical industry. The latter industry and its products, including plastics, oils and resins, chemical fertilizers and synthetic rubber, would in turn have important linkages to the development of other sectors of the economy, including as we have seen, the automobile and aircraft industries and the transformation of US agriculture.[27]

As the US economy became more energy-intensive during the twentieth century, it also increased its use of raw materials, such as industrial minerals, metals, agricultural and wood products, nonrenewable organics and crushed stone, sand and gravel. In a modern economy, material and energy use is inexorably linked. For example, the construction and maintenance of paved roads for automobiles and other motorized transport requires more crushed stone, sand and gravel, and the demand for these road-building materials requires additional freight transport. Increased electrification allows improvement in mining and extractive technologies, and the processing of the resulting minerals and ores, as well as the creation of improved alloys, entail more energy use.[28] As a consequence, nonfuel material use in the US economy also increased exponentially throughout the twentieth century. But the composition of US material use also changed, from renewables to nonrenewables. In 1900, about 41 percent of total material use came from renewable resources, such as agricultural, fishery, forestry and wildlife products. But by 1950, the share of renewable resources had declined to just 10 percent of overall material use. By 2000, materials from renewable resources accounted for just 5 percent of material consumption in the US economy, and nonrenewables 95 percent.[29]

The Industrial Revolution changed the structural dependence of a modern economy on its natural resource base, but the global frontier expansion and exploitation continued unabated. During the fossil fuel age, innovation and enhanced productivity have typically enabled more prosperity and economic growth, and more, not less, natural resource use. For example, although modern economies became increasingly less dependent on agriculture, throughout the Industrial Revolution considerable global land use change continued to occur. From 1750 to 1970, global forest and woodland area declined by over 6 million km^2, and savannah and grassland by 4.5 million km^2, as cropland area expanded dramatically.[30] In 1750, global cropland area occupied around 5.5 million km^2, and it tripled to 17.5 million km^2 by 1970. Despite the growth in productivity from new techniques, mechanization, high-yielding varieties and modern inputs; increasing human and livestock populations, changing diets and rising demand for food, fiber and fodder meant that more and more cropland needed to be found for "feeding the world."[31]

The fossil fuel age has also led to more, rather than less, exploitation of global freshwater resources. The hallmark of the modern era has been to try to meet every new demand for water – whether it is for agricultural or municipal and industrial use, for domestic food production or expanding exports to other countries – by finding and harnessing new supplies of freshwater. This has been the "hydraulic mission" of the modern era, and it was made possible by the considerable technological advances, economic wealth and energy resources generated by the Industrial Revolution. The global spread of industrialization further cemented the association between economic progress and increased water appropriation, control and use. As a consequence, in modern economies, water use management, and its accompanying innovations, institutions and incentives, is dominated by this "hydraulic mission" of finding and exploiting more freshwater resources.[32]

Water has always been critical for agriculture. In fact, water is still predominantly used for growing crops and raising livestock, which today accounts for 70 percent of water withdrawals globally, and 81 percent in low-income countries.[33] So as agriculture expanded worldwide from 1750 onward, so did global water use. Water has typically been treated as a plentiful and "free input" to agricultural production, much like other natural resources such as soils and energy from the sun. Because of this, there was little development of water markets for trade, and no incentive to treat water as a scarce capital asset to be managed and conserved.

Industrialization also brought rapid expansion of cities and urban populations, leading to additional demands for increased water use and sanitation. During the eighteenth and nineteenth centuries, spreading urbanization and rising population densities caused major water pollution problems and threats of deadly water-borne diseases, such as cholera and typhoid. As cities in Europe, North America and the rest of the industrializing world grew, they struggled to provide adequate clean water and sanitation on a large scale for their numerous residents.

To cope with these growing demands, cities developed extensive public infrastructure and water supply systems, often drawing on multiple freshwater sources across vast distances. Thus, the development of modern publicly funded urban water systems was both a consequence of and necessary for the growth of large cities, increasing urban populations and industrial expansion. More importantly, it solidified the modern mindset that solving the problem of large-scale water use and waste disposal is largely an engineering problem. The bigger the city and its population, the more clean drinking and other water supplies must be found, and the quicker and more efficiently the resulting volumes of waste water must be channeled away and disposed of away from urban areas. As industrialization has spread, and cities and populations expanded, so has this vast water supply and processing system. Today, the global water infrastructure supporting large cities supplies 668 million liters of water daily, and although these cities occupy only 1 percent of the Earth's land surface, their total sources of water cover 41 percent of that surface.[34]

The expansion of fossil fuel use, industrialization and cities also created a new environmental problem – local and regional air pollution. The energy economist Roger Fouquet has documented the rise of British coal consumption and air pollution from 1820 through the twentieth century.[35] Rapid coal use caused large environmental damages during the First Phase of the Industrialization, when coal was the dominant fossil fuel and Britain the leading industrial power (see Figure 2.2).

Coal consumption rose from 20 million metric tons in 1820 to 160 million in 1900. Air pollution also grew significantly over this period. In London, the concentration of total suspended particulates in the air increased from just under 400 micrograms per cubic meter (μg/m^3) in 1800 to 600 μg/m^3 in 1890.[36] This expanding coal use caused numerous deaths through lung disease and accidents to miners and air pollution in cities. Fouquet estimates that the value of lives lost amounted to 4 percent of Britain's GDP in 1820; climbed to 9 percent by 1850; and then peaked at 20 percent of GDP between 1870 and 1890.

Marine fishing and its surrounding coastal and marine environment were also transformed by industrialization and increased fossil fuel use.[37] Industrialization in the eighteenth and nineteenth centuries, along with the development of railways, steam-driven trawlers and ice storage, led to the global expansion of commercial marine fisheries. From the 1930s onward, diesel-powered trawlers and mechanization of fishing gear dominated the global industry. In just twenty years, marine fish catch more than tripled, from 14 million metric tons in 1950 to 53 million metric tons in 1970.[38] Overfishing inevitably ensued, with consequent destruction and degradation of marine, estuarine and coastal habitats and food webs. For example, the marine scientist Heike Lotze and colleagues have estimated that, in 12 once diverse and productive estuaries and coastal seas worldwide, fishing and other human impacts have depleted more than 99 percent of formerly important species; destroyed more than 65 percent of seagrass beds and wetland habitat; degraded water quality; and accelerated species invasions during the past 150–300 years.[39]

To summarize, during the fossil fuel age from 1750 to 1970, industrialization, mechanization and fossil fuel consumption led to extraordinary leaps in economic development, population levels, material living standards, life expectancy and quality of life for humans worldwide. But these same factors also caused massive environmental impacts, not just locally and regionally but increasingly on a planetary scale. In the twentieth century, despite two world wars and a global economic depression, the magnitudes of global environmental change of both the human drivers and their impacts were significant (see Table 2.3). However, it has really been since 1970, that both these drivers and their environmental impacts accelerated, during the current era of the "Great Acceleration."

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Table 2.3. Magnitudes of global environmental change, 1890s to 1990s

Indicator	Coefficient of increase, 1890s to 1990s
Drivers	
Human population	4
Urban proportion of human population	3
Total urban population	14
World economy	14
Industrial output	40
Energy use	13–14
Coal production	7
Freshwater use	9
Irrigated area	5
Cropland area	2
Pasture area	1.8
Pig population	9
Goat population	5
Cattle population	4
Marine fish catch	35
Impacts	
Forest area	0.8 (20% decrease)
Bird and mammal species	0.99 (1% decrease)
Fin whale population	0.03 (97% decrease)
Air pollution	2–10
Carbon dioxide (CO_2) emissions	17
Sulfur dioxide (SO_2) emissions	13
Lead emissions	8

Sources: Adapted from McNeill (2000, pp. 360–361) and McNeill (2005, tables 1 and 2).

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The Great Acceleration

This current era, which began in the late twentieth century, is the "Great Acceleration" of population growth, industrialization and mineral and energy use.

The term "Great Acceleration" was first coined by the working group of a 2005 conference on the history of the human–environment relationship.[40] However, it was really inspired by the long-term trends of human drivers and their global environmental impacts compiled by the International Geosphere-Biosphere Programme (IGBP) – the so-called Great Acceleration graphs – that illustrate how human impacts on the planet have accelerated in the second half of the twentieth century compared to the long-run trends since 1750.[41]

The most significant aspect of this era is the "acceleration" of four critical human threats to the global environment – climate change, land use and biodiversity loss, freshwater scarcity and deteriorating marine and coastal habitats. Figure 2.3 depicts some of the key trends that have defined the Great Acceleration of human activity and its impacts on the biosphere.

Since 1970, trends in agricultural production, fish harvest, freshwater use, bioenergy production and harvest of materials have increased, in response to population growth, rising demand and technological development. Over this period, the global human population has more than doubled (from 3.7 to 7.6 billion), rising unevenly across countries and regions; and per capita gross domestic product is four times higher – with ever-more distant consumers shifting the environmental burden of consumption and production across regions.[42]

As shown in Figure 2.3, from 1970 to the present, the expansion of energy use, carbon dioxide and fisheries production has been even greater than the doubling of global population. Freshwater use has largely kept pace with population growth. Global agricultural land use has expanded more modestly, by 30 percent. However, in low- and middle-income countries the expansion in crop and pasture land has been more significant, over 45 percent since 1970.

Land use change, habitat destruction and biodiversity loss in the tropics are primarily driven by the ongoing demand for agricultural production, mining and timber in these regions. As a consequence, tropical natural forests have declined by 11 percent since 1990.[43]

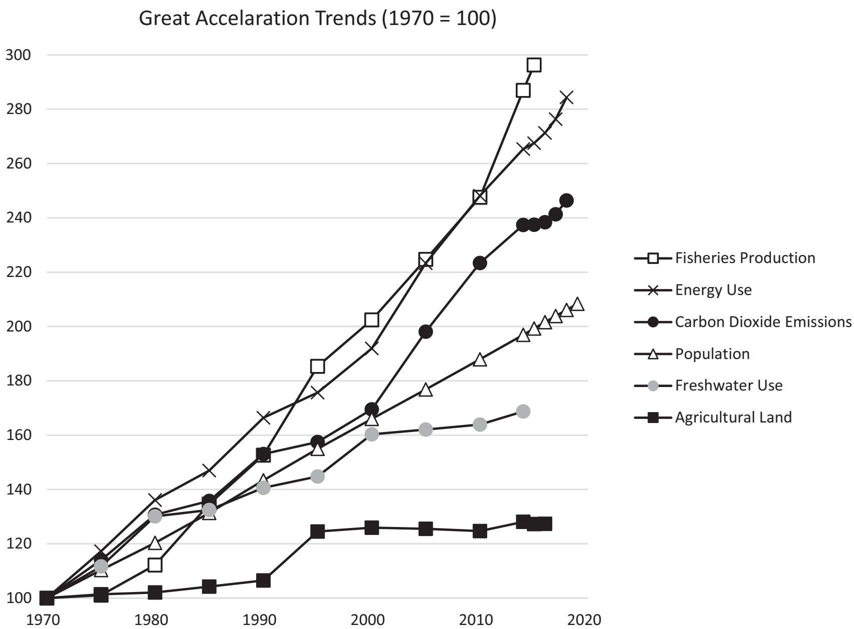

Figure 2.3 Key Great Acceleration trends since 1970
Source: Fisheries production (volume of aquatic species caught for all commercial, industrial, recreational and subsistence purposes); population (total global population); and agricultural land (land area that is arable, under permanent crops and under permanent pastures) are from World Bank, World Development Indicators https://databank.worldbank.org/reports.aspx?source=world. Energy use (primary energy consumption) is from BP Statistical Review of World Energy www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html. Carbon dioxide emissions (CO_2 emissions from fossil fuels and cement) is from Le Quéré et al. (2018). Global Carbon Project; Carbon Dioxide Information Analysis Centre (CDIAC) www.globalcarbonatlas.org/en/CO2-emissions; Freshwater use (global freshwater withdrawals, cubic meter per year) is from Hannah Ritchie and Max Roser (2017) – "Water Use and Stress." Published online at OurWorldInData.org: https://ourworldindata.org/water-use-stress

At the same time, since 1970, we have experienced a 60 percent decline in the populations of mammals, birds, fish, reptiles and amphibians.[44]

The nearly threefold rise in fisheries production over the past several decades is one reason why marine life is on the brink of a precipice. At least one-third of fish stocks are now overfished; one-third to half of vulnerable marine habitats have been lost; and a substantial fraction of the coastal ocean suffers from pollution, eutrophication, oxygen depletion and is stressed by ocean warming.[45] An additional

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disturbing trend in recent decades has been the exponential growth in marine plastic pollution. In 1970, there was an estimated 30,200 tonnes of plastics floating in global oceans. By 2020, this amount had risen to nearly 1.2 million tonnes.[46]

Because of this mounting toll on the global environment, some scientists are warning that humans are now on the verge of altering the Earth system irrevocably. Unless the Great Acceleration of human impacts on the global environment is slowed down, and possibly halted, we are becoming perilously close to inflicting significant and long-lasting changes to the entire Earth system. The Great Acceleration, which is the hallmark of the Anthropocene Age, has led to increased prosperity for most, but at the expense of growing environmental risks and even the threat of transcending *planetary boundaries*.

Planetary Boundaries

Humans have flourished on Earth for the last 12,000 years, thanks to the relatively stable and supportive environmental and climatic conditions of the Holocene era. This favorable global environment has enabled agriculture to evolve and expand; industrialization and complex human societies to emerge; and economies and trading networks to develop and multiply. This has also led to wealth and prosperity for many, but not all. At the same time, such economic gains have been achieved through unsustainable extraction of our natural resources; pollution of our lands, water and air beyond their ability to assimilate it; and the conversion and alteration of ecological functions and systems at the local, regional and global level.

Because humans now dominate the Earth system, we have entered a new era – the Anthropocene. Our actions are altering the global environment and we control its fate. As the previous section has documented, this Great Acceleration of human activity and impacts shows little signs of abating. This has several implications. We could be on the verge of altering the Earth system irrevocably and disrupting its stable Holocene-like state. We could be entering an "uncertain" Anthropocene, with unpredictable environmental consequences and possibly irreversible, damages to ecosystems, society and economies. We could end up in a "catastrophic" Anthropocene, with global warming of 2–4°C or more, massive biodiversity losses and species extinction, chronic freshwater scarcity and other unknown environmental disruptions.[47] Under

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these conditions, our planet may no longer be a hospitable and supportive environment for human habitation and well-being.

Avoiding these outcomes and producing a relatively "safe" Anthropocene is the greatest challenge facing humankind today. Some scientists suggest that, to protect key Earth system elements and processes, major human impacts on the global environment should be kept within *planetary boundaries*. Establishing such boundaries is the only way to avoid exceeding "tipping points" or "thresholds" that could lead to irrevocable changes in the entire Earth system, with potentially catastrophic impacts for humanity.[48]

Proponents of this view identify nine impacts resulting from human activity that should be subject to planetary boundaries:

- Climate change
- Loss of biosphere integrity (e.g. marine and terrestrial biodiversity loss)
- Land system change (e.g. land use change, such as deforestation and land degradation)
- Freshwater use
- Biochemical flows (e.g. effluents that interfere with nitrogen and phosphorous cycles)
- Ocean acidification
- Atmospheric aerosol loading
- Stratospheric ozone depletion
- Novel entities (e.g. new substances and modified organisms that have undesirable environmental impacts, such as toxic chemicals and plastics)[49]

If unchecked, each of these impacts on the global environment could place human population growth and economic activity on an unsustainable trajectory that crosses critical thresholds and destabilizes the entire Earth system. This could endanger its capacity to support and sustain humanity. According to the scientist Will Steffen and colleagues, establishing planetary boundaries for these nine impacts "aims to help guide human societies away from such a trajectory by defining a 'safe operating space' in which we can continue to develop and thrive."[50] It is also important that the boundary defining the safe operating space for human activities should include a "buffer" that both accounts for "uncertainty in the precise position of the threshold" and "also allows society time to react to early warning signs that it may be approaching a threshold and consequent abrupt or risky change."[51]

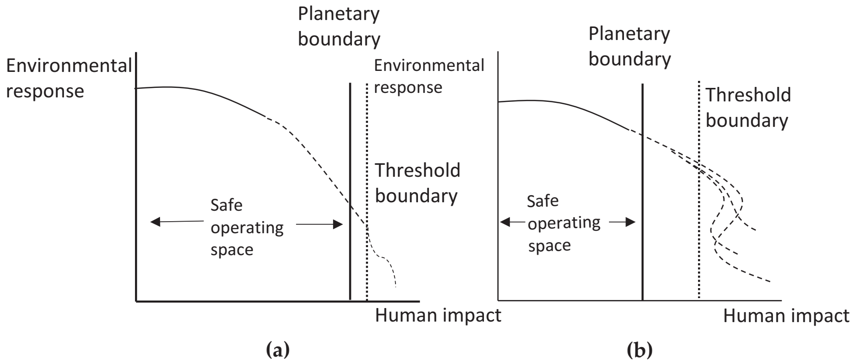

Figure 2.4 Establishing a planetary boundary
Notes: Past environmental responses (solid line curve) to a human-induced impact are unlikely to provide a good indication of future responses (dotted line curves), and uncertainty over irreversible threshold effects makes it difficult to predict the threshold boundary (vertical dotted line). To avoid unknown "tipping points" that lead irreversibly to these undesirable effects, scientists recommend establishing a planetary boundary (vertical solid line) well before any unpredictable threshold effects in environmental response could start occurring. Thus, a planetary boundary defines a finite safe operating space for human activity and its environmental impacts. Panel (a) illustrates the case when there is less uncertainty associated with predicting future threshold effects, so that the planetary boundary can be established relatively close to the predicted threshold boundary. Panel (b) illustrates the alternative case where there is considerable uncertainty over threshold effects, and so the planetary boundary should be set well before any possible threshold boundary.

Figure 2.4 illustrates how setting a planetary boundary to limit a key human impact on the global environment should take into account the uncertainty over possible future threshold effects.

The planetary boundary framework clearly aims to put a break on the environmental degradation associated with the Great Acceleration. Specifying a planetary boundary to demarcate a "safe operating space" for each of the nine human impacts listed will place an absolute limit on human exploitation of critical global biophysical sinks or resources. For example, various advocates of this approach have proposed boundaries to restrict depletion of terrestrial net primary production, freshwater, species richness, assimilative capacity for various pollutants, forest land area and the global carbon budget for 1.5°C or 2.0°C warming.[52]

However, as Table 2.4 indicates, some scientists may believe that we may be already perilously close to – and may even have

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Table 2.4. Suggested planetary boundaries and current human impacts

Planetary Boundary	Indicator of Human Impact	Pre-industrial Value	Current Value	Boundary Value[a]	Zone of Uncertainty[b]
Climate change	Atmospheric CO_2 concentration	280 ppm	398.5 ppm	350 ppm	450 ppm
Terrestrial biodiversity	Biodiversity intactness index	100%	84.6%	90%	30%
Land system change	Area of forested land remaining	100%	62%	75%	54%
Phosphorous (P) cycle loading	P flows from fertilizers, eroded soils	0 Tg P yr^{-1}	14 Tg P yr^{-1}	6.2 Tg P yr^{-1}	11.2 Tg P yr^{-1}
Nitrogen (N) cycle loading	Industrial and intentional biological fixation of N	0 Tg N yr^{-1}	150 Tg N yr^{-1}	62 Tg N yr^{-1}	82 Tg P yr^{-1}
Ocean acidification	Carbonite ion concentration aragonite saturation compared to pre-industrial	100%	84%	80%	70%
Freshwater use	Consumptive blue water use	~0 km^3 yr^{-1}	2,600 km^3 yr^{-1}	4,000 km^3 yr^{-1}	6,000 km^3 yr^{-1}
Aerosol loading	Aerosol optical depth	0.17	0.30	0.25	0.50
Stratospheric ozone depletion	Total column ozone at mid-latitudes	290 DU	2.2% reduction	5% reduction	10% reduction

Notes: [a]Planetary boundary defining a safe operating space for human activity and its environmental impacts (i.e. the vertical solid line in Figure 2.4); [b]Upper bound of a "zone of uncertainty," a range of increasing risk beyond the boundary value (i.e. the vertical dotted line in Figure 2.4); ppm = parts per million; DU = Dobson unit, a unit of measurement of the amount of a trace gas in a vertical column through the Earth's atmosphere.
Sources: Lade et al. (2020) and Steffen et al. (2015)

exceeded – the planetary boundaries for some human impacts. For example, for carbon dioxide emissions, remaining forest area and aerosol loading, we may have transcended the safe operating space for human activity and may have entered the "buffer zone" where unpredictable threshold effects could occur. Worse still, we may have already overloaded the global nitrogen and phosphorous cycles.

In addition, interactions among these various impacts may amplify their effects on the Earth system. For example, global forest loss can lead to greater carbon dioxide and other greenhouse gas emissions, increasing carbon dioxide–equivalent emissions in the atmosphere, and thus exacerbating climate change. Equally, a changing climate disrupts precipitation and causes temperature rises, which can reduce the amount of freshwater available for human use. As Steven Lade and colleagues found, this can lead to important trade-offs between the safe operating space available for some human impacts. For example, if carbon dioxide (CO_2) emissions are low, then high levels of agricultural activity are safe and vice versa. But high levels of both CO_2 emissions and agricultural activity cannot be safely maintained.[53]

However, some scientists are critical of the planetary boundary framework. One argument is that, although there is convincing evidence that human drivers can cause regime shifts at local and regional scales, the evidence for planetary tipping points in the terrestrial biosphere remains unconfirmed.[54] With the exception of climate change, which is inherently a global phenomenon caused by greenhouse gases emitted worldwide, most environmental change occurs locally and has mainly regional impacts. What is more, key environmental sources and sinks – from ecosystems and biodiversity to freshwater to nitrogen and phosphorous – are not distributed equally across the world. Thus, it does not make sense to have globally prescribed limits for most of the human impacts on the biosphere. Instead, policies and incentives should be targeted at limiting those impacts that are leading to excessive and destructive loss of the environment and growing risks. Or, as the ecologists José Montoya, Ian Donohue and Stuart Pimm maintain, to control most environmental impacts, "the focus must be on appropriate scales and variables that we can measure operationally," whereas in contrast, "the boundaries framework lacks clear definitions, or it has too many conflicting definitions, does not specify units, and fails to define terms operationally, thus prohibiting application by those who set policy or manage natural resources."[55] In practice, local, regional and global management is not necessarily mutually exclusive, and management at one level can reinforce it at another.

To be clear, none of the scientists who debate the relevance of planetary boundaries are questioning whether the Great Acceleration in human impacts on the biosphere is causing massive harm to the Earth's climate, oceans and lands.[56] For example, a critic of the planetary boundary framework, Stuart Pimm, was one of the first to demonstrate that the rate of extinction of species due to the exploitation of the planet by people is 100–1,000 times higher than prehuman extinction.[57] And, along with his fellow critics Montoya and Donohue, Pimm goes on to argue that "mounting evidence demonstrates the patterns and mechanisms by which biodiversity loss alters the provision of functions and the stability of ecosystems. We can now assess and monitor how losses in biodiversity affect different ecosystems. This in turn allows the effectiveness of a given environmental policy to be determined."[58] Equally, in reviewing the scientific evidence for and against tipping points in the terrestrial biosphere, Timothy Lenton and Hywell Williams conclude that "regardless of whether it is approaching a global tipping point, we can all agree that the biosphere is in trouble."[59]

In addition, as noted in the Chapter 1, there are also many equity and development concerns about imposing any limits on human exploitation of critical global sinks and resources inherently.[60] If current access to these sinks and resources is unequally distributed and dominated by wealthy nations, regions and individuals, then additional policies may be necessary either to improve access by the poor or to ensure that they are adequately reimbursed for any additional burdens imposed by reduced access.

Finally, some may believe that the COVID-19 pandemic and the resulting downturn in the world economy have mitigated human impacts on the biosphere. But evidence suggests that any respite has either been short-lived, or for some impacts, even worse during the outbreak. There was a temporary fall in global greenhouse gas emissions in 2020, when the world economy stagnated, but emissions are returning to previous levels as the past pattern of global economic development and energy use resumes.[61] On the other hand, land clearing for mining, agriculture, forestry and other commercial activities – often illegal – increased significantly during the pandemic, as governments diverted resources to COVID-19 or failed to protect remote regions. In 2020, the world lost more than 4.2 million hectares in tropical primary forest, which is a 12 percent increase over the area cleared in 2019.[62] The pandemic has also caused rising debt levels and budget cuts in low- and middle-income countries, which has affected their management, protection and restoration of natural areas and ecosystems.

As global environmental risks continue to multiply, we urgently need policies and actions to save the biosphere. Science shows us that the Earth system provides natural resources, pollution sinks, ecosystem services and essential life-support functions. This natural capital plays an essential role in human survival and well-being. Due to misuse and overexploitation, global natural capital is becoming increasingly scarce and fragile, and the Earth system itself may be in danger of destabilization. Institutions and incentives for investment, innovation and improved management of Earth's valuable natural capital is critical. This is where economics can contribute, and the five principles outlined in Chapter 1 can help guide our policies and actions. The rest of the book explains what should be done to ensure a safer and more prosperous Anthropocene.

Notes

1 See Crutzen (2002); Crutzen and Stoermer (2000); McNeil and Engelke (2016); Steffen et al. (2011); and Waters et al. (2016).
2 Further discussion of key eras of how human economies developed through natural resource exploitation, and the impact on the global environment, can be found in Barbier (2011). For more details, please see the many references cited in this work.
3 See Smith et al. (2010). This article is one of a series of papers appearing in a special section of *Current Anthropology* from a detailed and comprehensive study of the transmission of wealth and inequality in prehistoric societies, including hunter-gatherer and early agricultural societies.
4 The classic treatise on the domestication of animal and plant species and the impact on early human society is Diamond (1997). See also Barbier (2011), chapter 2 and Bellwood (2005).
5 For an excellent summary of recent research on this process, see Deborah Rogers. "Inequality: Why egalitarian societies died out." *NewScientist* July 25, 2012. Available at www.newscientist.com/article/dn22071-inequality-why-egalitarian-societies-died-out.
6 The idea that environmental degradation was a proximate cause of the collapse of many empires and civilizations is controversial, yet is gaining prominence. Yoffee (1988) credits the environmental writer, Rice Odell, for first postulating in the mid-1970s the thesis that "environmental degradation" was "among the most important and best attested of the proximate causes of collapse" of states and civilizations. More recently, Diamond (2005) has popularized the notion that ecological degradation and collapse were responsible for the eventual demise of many ancient civilizations. However, this "environmental collapse" thesis has been criticized as

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oversimplifying societal decline, which is complex and rarely attributable to a single cause; see Butzer (2012) and Haldon et al. (2018).

7 Based on Maddison (2003), tables 8a and 8b.

8 This was, after all, the age of the Black Death and numerous other plagues that were spread via trade and the corresponding movement of people, goods and animals. For example, the bubonic plague – the Black Death – appears to have been brought by overland routes from Central Asia to China, where it caused successive cycles of epidemics until as late as 1393, while at the same time moving westward to the Middle East and Western Europe via the old Silk Roads as well as the new spice trade sea routes. The Black Death spread quickly in the Western Hemisphere. It reached Crimea by 1345, and Constantinople, Alexandria, Cairo, Cyprus and Sicily in 1347; from there it spread to the great ports of Pisa and Genoa and the rest of Europe via southern France. By 1351, the plague had largely died out in the Western Hemisphere.

9 From Maddison (2003), table 8.b. Maddison's estimates for 1500 indicate that China's share of world gross domestic product (GDP) was 24.9 percent; India's share was 24.4 percent; and Western Europe's share was 17.8 percent. GDP per capita was $600 in China; $550 in India; and $771 in Western Europe, of which the main economies were France, Germany, Italy, the Netherlands, Spain and the United Kingdom.

10 Jones (1987), pp. 80–82.

11 Crosby (1986).

12 Engerman and Sokoloff (1997). Slavery was critical to the new "Atlantic economy" that emerged between 1500 and 1860. As described by Findlay (1993, p. 322), "the pattern of trade across the Atlantic that prevailed from shortly after the time of the discoveries down to as late as the outbreak of the American Civil War came to be known as the 'triangular trade', because it involved the export of slaves from Africa to the New World, where they produced sugar, cotton, and other commodities that were exported to Western Europe to be consumed or embodied in manufactures, and these in turn were partly exported to Africa to pay for slaves." This "triangular trade" corresponded to its own unique pattern of European exploitation of the abundant land and natural resource frontiers of the New World (for more details, see Barbier 2011, chapter 6). For example, Inikori (1992, p. 152) argues that "the growth of Atlantic commerce during the period was a function of commodity production in the Americas," and virtually all the key export commodities of the region were produced by slave labor – gold, silver, sugar, coffee, cotton, tobacco and rice. Moreover, Inikori (1992, p. 155) adds: "The importance of African slavery to Atlantic commerce went beyond the production of the American commodities that were traded. The forced migration of millions of Africans to the extremely low-density territories of the Americas, where they were forced to produce export commodities, provoked an Atlantic-wide division of labor that was the very foundation of Atlantic commerce." This division of labor had two consequences. First, it created an "extractive" frontier of export-oriented commodities in tropical Latin America and the southern US, which contrasted with the emerging and largely subsistence "settlement" frontiers of North America. Second, "the violent production of captives for export to the Americas became virtually the only function performed by western Africa in the Atlantic system."

13 Acemoglu et al. (2001), p. 1373.

14 Acemoglu et al. (2001), p. 1370. A point ignored by Acemoglu et al. (2001) but emphasized by others, notably Crosby (1986), Diamond (1999) and Livi-Bacci (1997), is that disease and environmental conditions also played an important role

in the success of European colonization. That is, by bringing in imported diseases from Europe, such as smallpox, tuberculosis and measles, European colonists effectively decimated many indigenous populations who had no genetic resistance to such diseases. This further enhanced the ability of Europeans to establish successful colonies, regardless of whether they were in temperate regions with permanent settlements by Europeans or "extractive states" with minimal settlement in tropical climates.

15 Crosby (1986, pp. 3–7) coined the term "neo-Europes," which he identifies as lands that "are all completely or at least two-thirds in the temperate zones" and in which people of European descent "compose the great majority" of the present-day population. Note that Crosby's definition also poses some problems for identifying which countries and regions in temperate South America are truly "neo-Europes." For example, Argentina, Uruguay and southern Brazil (Paraná, Santa Catarina and Rio Grande du Sul) fit both his criteria and are included. However, Chile does not and appears to be excluded: "In contrast, Chile's people are only about one-third European; almost all the rest are *mestizo*" (Crosby 1986, p. 3). Curiously, Crosby simply ignores Paraguay, even though at least half of its territory lies below the Tropic of Capricorn, and like southern Brazil, the majority of the population in the region is mainly of European descent. Despite these difficulties in identifying which of the present-day countries of South America quality as "neo-Europes," Crosby (p. 3) concludes: "But if we consider the vast wedge of the continent poleward of the Tropic of Capricorn, we see that the great majority are European."

16 See, for example, Barbier (2011), chapter 5; Chew (2001); Elvin (1993); Hughes (2001); McNeill (1998); and Richards (2003).

17 Richards (2003), pp. 26–38.

18 Richards (2003), pp. 617–618.

19 Toynbee (1978), p. 566.

20 See Thomas (1985) and Wrigley (1988).

21 In depicting the Industrial Revolution as two distinct phases (see also Figure 2.2), I am following the pioneering long-run analysis by Gordon (2017). In addition, Gordon contends that there was a third phase of the Industrial Revolution with the computer and internet revolution that began around 1960 and reached its climax in the dot.com era of the late 1990s, but its main impact on productivity was short-lived, lasting until the 2010s. However, none of these phases of the Industrial Revolution has allowed any economy to transition from the fossil fuel age.

22 Smil (2005), p. 28. See also Etemad et al. (1991); Fouquet (2008); and Smil (2010).

23 From Smil (1994) and (2010), except for the estimates for the 1970s, which is from BP (2019).

24 These historical statistics for global population and GDP per capita are from the Maddison Project Database, version 2018 (Bolt et al. 2018). Real GDP per capita is in US$ 2011.

25 Nelson and Wright (1992), p. 1945.

26 As noted by Nelson and Wright (1992), pp. 1944–1945, "The automobile industry was the most spectacular American success story of the interwar period, a striking blend of mass production methods, cheap materials, and fuels. Despite barriers to trade and weak world demand, U.S. cars dominated world trade during the 1920s, and motor vehicles dominated American manufacturing exports."

27 Nelson and Wright (1992), p. 1946. From the 1920s onward, the parallel development of the aircraft industry and air transport across the United States spurred further economic integration by increasing the mobility of people, cargo and even the mail. By 1950, total air traffic in the United States reached one billion miles,

which for the first time equaled total railroad mileage in the country. See Meinig (2004), pp. 87–96.

28 Both trends are noted by Smil (2006), p. 7 and pp. 87–88: "Intensifying traffic necessitated large-scale construction of paved roads, and this was the main reason for hugely increased extraction of sand, rock, and limestone whose mass now dominates the world's mineral production and accounts for a large share of freight transport … Rapid growth of aggregate material consumption would not have been possible without abundant available energy in general, and without cheaper electricity in particular. In turn, affordable materials of higher quality opened up new opportunities for energy industries thanks to advances ranging from fully mechanized coal-mining machines and massive offshore oil drilling rigs to improved efficiencies of energy converters. These gains were made possible not only by better alloys but also by new plastics, ceramics, and composite materials."

29 Wagner (2002), pp. 6–7 and figure 5. Wagner defines "nonrenewable organic materials" as all products derived from feedstocks of petroleum and natural gas and coal for nonfuel applications, including resins used in the production of plastics, synthetic fibers and synthetic rubber; feedstocks used in the production of solvents and other petro-chemicals; lubricants and waxes; and asphalt and road oil.

30 Ramankutty and Foley (1999), who reconstruct historical croplands, forest and woodlands, savannah and grasslands and abandoned cropland from 1700 to 1992. Their data was downloaded from the Global Land Use Database, Center for Sustainability and the Global Environment (SAGE), Nelson Institute for Environmental Studies, University of Wisconsin, www.sage.wisc.edu. In 1750, global forest and woodland area was 60 million km^2 and less than 47 million km^2 in 1970. Savannah and grassland was almost 32 million km^2 in 1750, and 27 million km^2 in 1970.

31 Federico (2005).

32 This evolving water resource management ethos that emerged from the Industrial Revolution is described succinctly by Saveniji et al. (2014), pp. 320–321: "The increased exploitation of freshwater and the related development of societies has been made possible by increasing knowledge of water engineering, large-scale water supply, flood mitigation and irrigation … Equipped with new technological powers, a new generation of engineers emerged that had a new hydraulic, mission: that of 'taming' nature and making it orderly … During the last decades of the 19th century and the first decades of the 20th century, the water landscape was transformed in various places, including but not limited to India, Sudan, Mali, Egypt, the USA, Brazil, Spain and the Netherlands. These developments, associated with large and powerful water bureaucracies … allowed for unprecedented growth in the production of agricultural commodities and energy and confirmed the belief that man could fully control water and be the master of nature" (pp. 320–321). As explained in Barbier (2019b), the continued pursuit of this "hydraulic mission" has had implications for the growing crisis in global water management today.

33 FAO (2012).

34 McDonald et al. (2014). This study focused on water use of a sample of urban agglomerations greater than 750,000.

35 Fouquet (2011).

36 As Fouquet (2011), p. 2383 notes: "For comparison, TSP concentrations for Delhi in the 1990s, one of the most polluted cities in the world, were around 370 μg/m^3."

37 See, for example, Jackson et al. (2001) and (2011); Lotze and Milewski (2004); Lotze et al. (2006); Pitcher and Lam (2015); and Roberts (2007).

38 From the "Great Acceleration" graphs of the International Geosphere-Biosphere Programme (IGBP), available at www.igbp.net/globalchange/greatacceleration.4

.1b8ae20512db692f2a680001630.html and also presented in Steffen et al. (2015a). Note that global marine fish catch reached its peak of 72–73 million metric tons between 1994 and 1997, and has since declined. By 2010, it had fallen to 64 million metric tons.

39 Lotze et al. (2006).

40 Hibbard et al. (2006). See also McNeil and Egelke (2016) and Steffen et al. (2007) and (2015a).

41 The original graphs can be found in Steffen et al. (2004) and (2007). These graphs and trends have been updated to 2010 by the IGBP and are available at their website www.igbp.net/globalchange/greatacceleration.4.1b8ae20512db692f2a680001630.html and also presented in Steffen et al. (2015a).

42 From IPBES (2019). However, Ellis et al. (2013) point out that, although human populations and land use have increased, agricultural intensification and the adoption of technologies enabling dramatic increases in food production from a given area of agricultural land have also risen in the modern era as populations have grown and become wealthier. They argue that agricultural intensification processes may be even more important to understanding the future of land use change as a force transforming the Earth system. This is an argument that we will be taking up again in Chapter 5.

43 Based on the Food and Agriculture Organization of the United Nations (FAO) Forest Resources Assessment (FRA) 2015 data, www.fao.org/forest-resources-assessment/explore-data/en.

44 WWF (2018).

45 Duarte et al. (2020).

46 Based on Hannah Ritchie (2019) "Where Does Our Plastic Accumulate in the Ocean and What Does That Mean for the Future?" Published online at OurWorldInData.org https://ourworldindata.org/where-does-plastic-accumulate. The original source of the data is Lebreton et al. (2019).

47 One such "catastrophic" Anthropocene outcome is the "Hothouse Earth" state described by Steffen et al. (2018).

48 Lenton et al. (2008) first postulated the possibility of tipping points or "elements" in the Earth's climate systems. A special issue edited by Schellnhuber (2009) then extended the concept to other Earth system processes. Rockström et al. (2009) used the possibility of such human-induced stresses on the Earth system to develop the "planetary boundaries" concept.

49 See, for example, Lade et al. (2020); Rockström et al. (2009); Steffen et al. (2015).

50 Steffen et al. (2015), p. 737.

51 Steffen et al. (2015), pp. 737–738.

52 See, for example, Dinerstein et al. (2017); Gerton et al. (2013); Lade et al. (2020); Mace et al. (2014); Newbold et al. (2016); Rockström et al. (2009); Running (2012); and Steffen et al. (2015).

53 Lade et al. (2020).

54 See, for example, Brook et al. (2013) and Montoya et al. (2018).

55 Montoya et al. (2018), p. 73 and p. 71. A similar criticism is made by the economist Alan Randall (2021, pp. 10–11), "The intuition for PBs can be defended most convincingly for global public goods. Several of the PBs [planetary boundaries] are of this kind: genetic diversity, with a PB that already has been violated; carbon and climate, in the amber zone; ocean acidification and atmospheric ozone depletion, with some SOS [safe operating spaces] intact; and atmospheric aerosol loading, with uncertain status. In all of these cases, the problem shed is global and a PB at global scale makes sense. The remaining PBs—freshwater use, land systems, ecosystem

integrity, and biochemical flows—are not, or at least not entirely, planetary in that the problem sheds tend to be more localized and most of the rewards for management at the problem-shed level are enjoyed at that level. Many problems concerning freshwater and biogeochemical flows are manifested and best managed at the watershed level. Land systems to feed the world may be a global issue, but urban greenspace is much more a local concern. It can be argued that for problems that are manifested mostly at the problem-shed level, there is ample scope and motivation for variation across problem sheds in place-based objectives, approaches, and solutions."

56 For a fascinating insight into the various arguments of this scientific debate, see Bob Lalasz. "Debate: What Good Are Planetary Boundaries?" Cool Green Science, March 25, 2013, available at https://blog.nature.org/science/2013/03/25/debate-what-good-are-planetary-boundaries.

57 Pimm et al. (1995).

58 Montoya et al. (2018), p. 73.

59 Lenton and Williams (2013), p. 382.

60 See, for example, Biermann and Kim (2020).

61 Andrijevic et al. (2020); Le Quéré et al. (2020); and Tollefson (2021).

62 See Mikaela Weisse and Liz Goldman. "Primary Rain Forest Destruction Increased 12% from 2019 to 2020." Global Forest Watch. March 31, 2021 www.globalforestwatch.org/blog/data-and-research/global-tree-cover-loss-data-2020.