Chapter 4
Human Impact on the Biosphere

Introduction

World population in 1950 was around 2.5 billion and global output of final goods and services, at 2011 prices, a little over 9.2 trillion international dollars (dollars at purchasing price parity, PPP) (Figures 4.1 and 4.2). As noted in Chapter 0, the average person's annual income was about 3,300 dollars PPP, a high figure by historical standards (Maddison, 2018) (Figure 4.3). Since then the world has prospered beyond recognition. Life expectancy at birth in 1950 was 46; today it is above 72. The proportion of the world's population living in absolute poverty (currently 1.90 dollars PPP a day) has fallen from nearly 60% in 1950 to less than 10% today (World Bank, 2020a). In 2019, the global population had grown to over 7.7 billion even while global income per capita had risen to 15,000 dollars PPP (at 2011 prices). The world's output of final goods and services was a little above 120 trillion dollars PPP (at 2011 prices), meaning that globally measured economic activity had increased 13-fold in only 70 years, none of which had been remotely experienced before (Chapter 0).

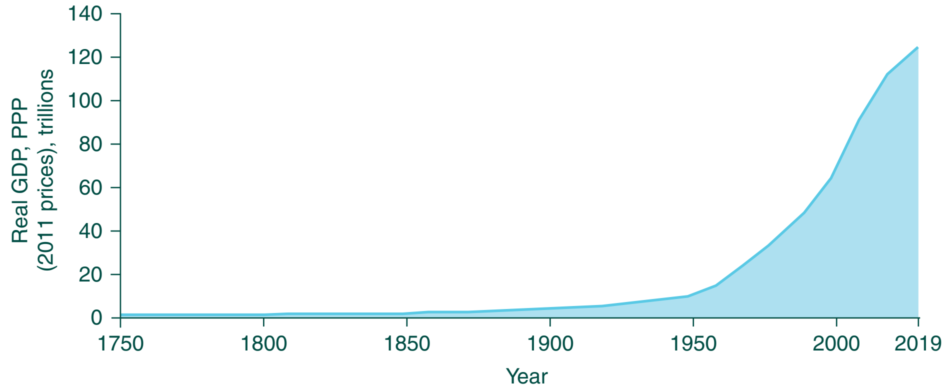
This remarkable achievement has, however, come in tandem with a massive deterioration of the biosphere. This chapter collates scientific evidence that points to this deterioration (Section 4.1) and then constructs a heuristic device for expressing the global demand for the biosphere's goods and services per unit of time and the rate at which the biosphere supplies them (Sections 4.2, 4.3 and 4.4). The latter could be thought of as the biosphere's regeneration rate.[114] We call the difference between demand and supply the *Impact Inequality* (Expression 4.1). That difference has been widening in recent decades. Because demand is decomposed in Expression (4.1) into its several factors, the Impact Inequality points to policy levers that can help steer the global economy toward equality between supply and demand on a sustainable basis, which would convert the Impact Inequality into an Impact Equality. Attaining Impact Equality should be a minimum requirement of the United Nations' Sustainable Development Goals (SDGs). The chapter offers a way to construct quantitative estimates of what has to happen as a minimum if the SDGs are to be sustainable.

4.1 Depreciating the Biosphere

In Chapter 2 (Box 2.3) we offered a qualitative argument, based on crude estimates of own rates of return on primary producers were presented and compared with own rates of return on composite baskets of financial assets to signal that global investments in recent decades have been enormously skewed against Nature. Three related types of evidence have been offered by environmental scientists and one (also related) by economists that vastly enrich that finding. They show that there has been, for some decades, an enormous overshoot in the demands we make of the biosphere.

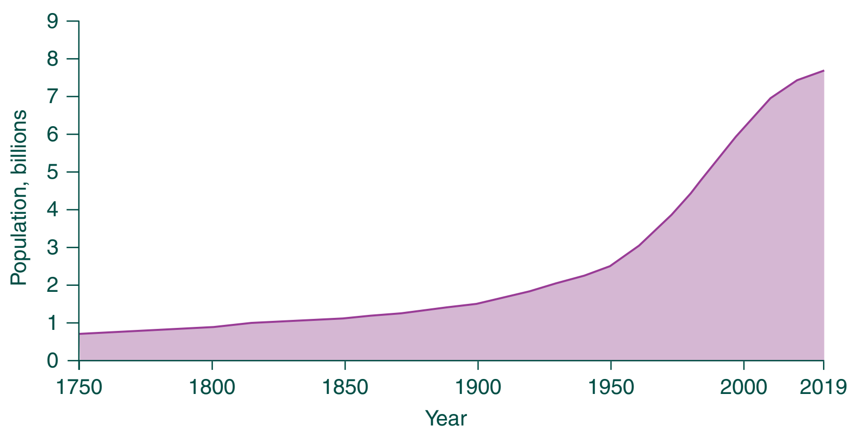
[114] We are taking literary licence here by speaking of the biosphere's regeneration rate, as non-living material does not regenerate, but rather is subject to processes that give rise to their rhythm over time. Steffen et al. (2011) present a synthesis of quantitative evidence since the middle of the last century of growth in humanity's demand for the biosphere's goods and services. The authors combine that with data on declines in the biosphere's health since then. Steffen et al. (2015b) describe that growth as the Great Acceleration.

Figure 4.1 Global Real GDP since 1750



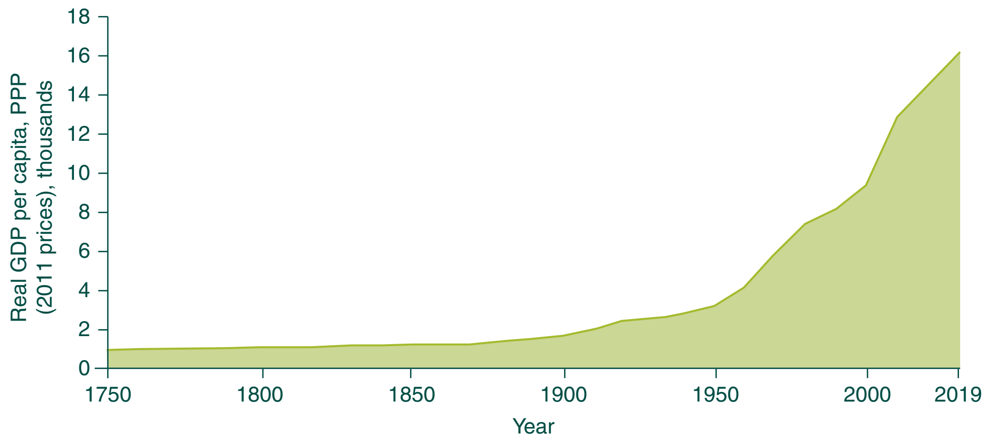
Source: Our World in Data based on World Bank (2020a), Maddison (2018), Bolt et al. (2018) and Review calculations.

Figure 4.2 Global Population since 1750



Source: Maddison (2010), United Nations Population Division (2019) and Review calculations.

Figure 4.3 Global Real GDP Per Capita since 1750



Source: Our World in Data based on World Bank (2020a), Maddison (2018), Bolt et al. (2018) and Review calculations.

4.1.1 The Anthropocene and Species Extinction

One route to examining our demand overshoot involves the study of the Earth's biogeochemical signatures. In a wide-ranging survey, Williams et al. (2015) divided the evolution of the biosphere into three stages: (1) a microbial stage from about 3.5 billion years ago to about 650 million years ago; (2) a metazoan stage, evident by 650 million years ago when the oxygen level in the atmosphere had begun to rise; (3) the modern stage, starting with the use of stone stools by our ancestral Hominids some 2.6 million years ago and accelerating since the beginnings of agriculture some 14,000 years ago. The authors characterise the current face of the modern stage as (i) global homogenisation of flora and fauna; (ii) a single species, *Homo sapiens*, commanding 25–40% of net primary production (NPP) and also mining fossil fuels to overcome photosynthetic energy constraints; (iii) human directed evolution of other species; and (iv) a rising and less modular interaction of the biosphere with the global human enterprise. The authors suggest that these features of today's biosphere point to a new era in the planet's history that could persist over geological timescales.

In a review of evidence from the past 11,000 years (the Holocene), Waters et al. (2016) have taken a closer look, by tracking the human-induced evolution of soil nitrogen and phosphorus inventories, and carbon dioxide and methane in sediments and ice cores. The authors reported that the now-famous figure of the 'hockey stick' that characterises time series of carbon concentration in the atmosphere is also displayed by time series of a broad class of global biogeochemical signatures (IPCC, 2018). They display a flat trend over millennia until some 250 years ago, when they begin a slow increase that continues until the middle of the 20th century, when they show a sharp and continuing rise. The trends in global economic activity over the past 70 years that we have summarised above and displayed in Figures 4.1 and 4.2 are entirely consistent with these findings.[115] Waters et al. (2016) suggested that the mid-20th century should be regarded as the time we entered the Anthropocene. Figure 4.4 summarises the time profile of key anthropogenic markers that are indicative of the Anthropocene.[116]

[115] Steffen et al. (2011) provide a more detailed account of deterioration in the biosphere's health since the beginning of the Industrial Revolution.

[116] The Anthropocene Working Group has proposed that the immediate post-war years should be regarded as the start of the Anthropocene (Voosen, 2016). Kolbert (2013a) contains an account of how stratigraphers uncover geological signatures of abundance and disappearance of species in the distant past.

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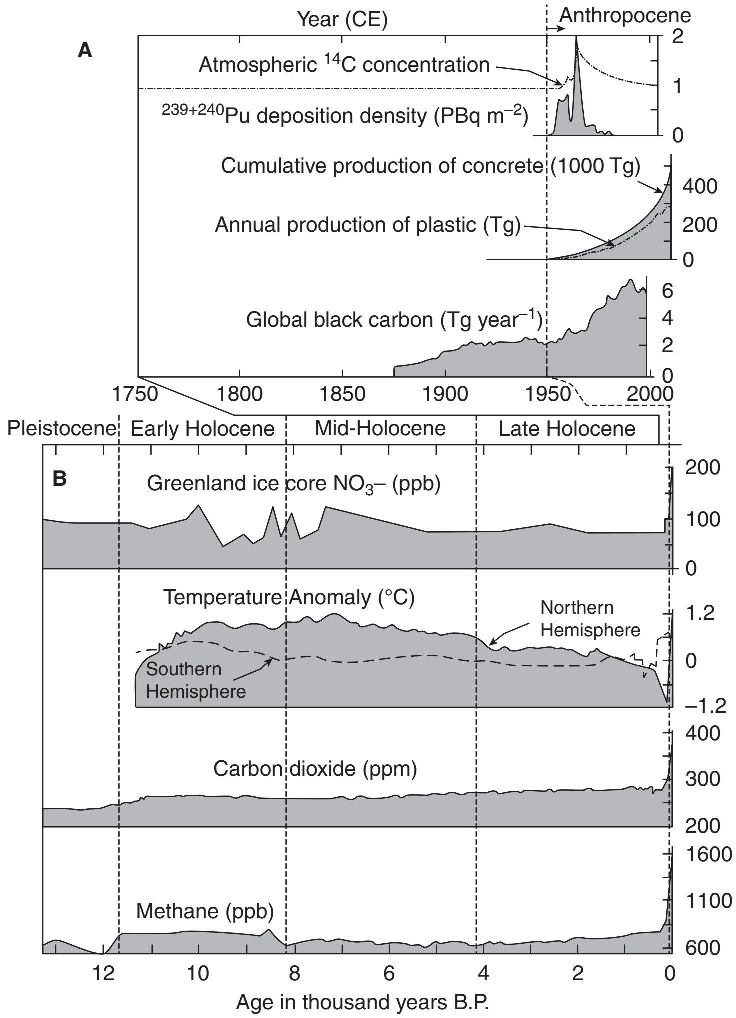
Figure 4.4 Magnitude of Key Markers of Anthropogenic Change Indicative of the Anthropocene



Source: Waters et al. (2016). *Permission to reproduce from The American Association for the Advancement of Science (AAAS).*

One indelible signature of the Anthropocene is species extinction. As noted previously, there are 8 to possibly 20 million or more species of eukaryotes, but only about 2 million have been recognised and named (Raven, 2020). Current extinction rates of species in various orders are estimated to have risen to 100–1,000 times the average extinction rate over the past tens of millions of years (the 'background rate') of 0.1–1 per million species per year (expressed as E/ MSY), and are continuing to rise.[117] In absolute terms, 1,000 species are becoming extinct every year if 10 million is taken to be the number of species and 100 E/MSY the current extinction rate.

Extinction rates are inferred from comparisons with fossil records in groups that have hard body parts, like vertebrates and molluscs, and from empirically drawn relationships between the number of species in an area and the size of the area (Box 4.1). But the latter relationships are known to vary

[117] See Wilson (2002, 2016), Sodhi, Brook and Bradshaw (2009), De Vos et al. (2014), Pimm et al. (2014), and Ceballos, Ehrlich and Ehrlich (2015).

substantially among communities and habitats, which is why, as the range shows, there are great uncertainties in the estimates. Despite the uncertainties, the figures put the scale of humanity's presence in the biosphere in perspective.[118] The figures also tell us why Earth scientists and ecologists say we are witnessing the *sixth* great biological extinction since life began.[119]

Judged by what is known about relatively well-studied groups (terrestrial vertebrates, plants), some 20% of the species could become extinct within the next several decades, perhaps twice as many by the end of the century. It is estimated that 84 mammal species have become extinct since 1500 and 32 species of mammal have gone extinct since 1900 (IUCN, 2020; Pimm and Raven, 2019).[120] In their recent survey of population data on nearly 30,000 species of terrestrial vertebrates, Ceballos, Ehrlich and Raven (2020) have estimated how many are on the brink of extinction. Their criterion was populations with fewer than 1,000 individuals. By this measure, 515 species are on the brink, representing 1.7% of the vertebrates on the authors' survey list. If extinction follows at the same rate, the population of terrestrial vertebrates will halve in about 40 years. But the rate is likely to increase at an accelerated rate, for several reasons. First, human pressure on the biosphere is increasing (see below); second, the distribution of those species on the brink coincides with hundreds of other endangered species, surviving precariously in regions with high human impact; and third, close ecological interactions among species tend to move other species toward annihilation – extinction breeds extinction. Assuming all species on the brink have experienced similar trends, the authors estimate that more than 237,000 populations of those species have vanished since 1900.

Box 4.1
Deforestation and Species Extinction

Human induced habitat destruction is today the leading cause of species extinction. A quarter of all tropical forests have been cut since the Convention on Biodiversity (CBD) was ratified 27 years ago. Pimm and Raven (2000) observed that generally speaking, many of the species found across large areas of a given habitat reside in small areas within it. That means habitat loss initially causes few extinctions, but the numbers rise as the last remnants of habitat are destroyed. At current rates of habitat destruction, the peak of extinctions may not occur for a long while, even decades.

The above reasoning follows also from species-area graphs familiar from island biogeography, which have the broad features of power functions. Writing the number of species by S and area by A, their relationship can be approximated as a two-parameter power function

$$S = \alpha A^{\beta}, \alpha > 0, 0 < \beta < 1 \qquad \text{(B4.1.1)}$$

Rosenzweig (1995) reported that for birds, ants and plants β has been found to be in the region 0.2–0.8.[121] To see the salience of species-area relationships for estimating extinction rates, here

[118] Pimm and Raven (2019), in addition to providing the most recent estimates of extinction rates in various orders, includes an excellent overview of the methods that are deployed for estimating them. Wilson (1992), Wilson (2002, 2016) and Ehrlich and Ehrlich (2008) are expert dissections of the scale of the human presence in the biosphere. Dasgupta, Raven and McIvor (2019) is a collection of essays on biological extinctions, ranging from birds and mammals to microorganisms in the soils.

[119] The Sixth Extinction has also been extended in time and been called the Holocene Extinction, which began at the end of the last glacial period some 11,000 years ago, the signature being provided by the extinction of large land mammals. Kolbert (2014) is a narrative on the mass extinctions under way.

[120] We are grateful to Peter Raven for correspondence on this.

[121] The classic on this is MacArthur and Wilson (1967), which also provided an account of a process of immigration and emigration of which equation (B4.1.1) is an equilibrium.

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is a rough estimate of extinctions that can be expected from the continuing destruction of tropical rainforests.[122]

Of the approximately 10,000 bird species today, some 5,000 inhabit tropical rainforests. As a reasonable approximation we set $\beta = 0.25$ in equation (B4.1.1). Suppose a further 50% of tropical forests were destroyed in the next 100 years. It would mean a loss of about 13% of bird species there, which would amount to 650 species. Other things equal, extinction of 650 species of birds in 100 years out of a total of 10,000 species of birds yields a figure of 650 E/MSY. That is either 65 times or 650 times the background extinction rate, depending on whether that rate is taken to be 0.1 E/MSY or 1 E/MSY.

Suppose, however, that humanity is able to restrain itself in the future and limits the destruction of tropical forests to only a further 25%. That would mean an eventual extinction of 6% of bird species, that is, 300 species. That is either 30 times or 300 times the background extinction rate, depending on whether that rate is taken to be 0.1 E/MSY or 1 E/MSY.

Suppose for a moment too, that humanity is able to come to grips with species extinction and limits tropical deforestation to only a further 0.8% over the next 100 years. That would mean an eventual extinction of 0.1% of bird species, that is, 10 species. Even that is 10 or 100 times the background extinction rate, depending on whether that rate is taken to be 0.1 E/MSY or 1 E/MSY. It is clear that destruction of tropical rainforests has to come to a complete halt if the extinction rates of birds are to be brought down to anything like background rates of species extinction. And we have not accounted for the millions of other, uncounted species that are being extinguished in those forests and elsewhere.

Species-area relationships allow one to estimate, albeit very crudely, extinction rates that follow habitat destruction. But one can flip the reasoning and ask what limits should be set on habitat destruction if bounds are set on further species extinction. There is a temptation to do that because one can then set the bounds by relating them to the background rate, as we have just done (Rounsevell et al. 2020).

But it is doubtful that the line of reasoning is fruitful. Even expert knowledge is so incomplete about species numbers and their distribution and mix, that setting extinction bounds would not provide a guide to policy. For example, the recorded number of species of mites is around 45,000 and there may perhaps be 1 million more; of nematodes around 25,000 and 500,000 more; and of fungi round 100,000 and 2.2 to 3.8 million more (Mueller et al. 2007; Kiontke and Fitch, 2013; Walter and Proctor, 2013; Hawksworth and Lücking, 2017).[123] There is vast uncertainty in these numbers. Moreover, unlike habitats, species numbers cannot be observed directly. So, it is not possible to place bounds on species extinction rates as policy targets when the number of species lies within a large range (perhaps 8 to 20 million). In contrast, habitat destruction can be observed and verified. The approach taken by the CBD in the Aichi Biodiversity Targets of 1992, which was to set limits on habitat destruction and specify Protected Areas is in line with this reasoning. That the targets are far from being met is not a fault in reasoning, it is, as in the case of international targets on carbon emissions, an inability of countries to design an enforcement mechanism.

[122] We are indebted to Stuart Pimm for it in correspondence.

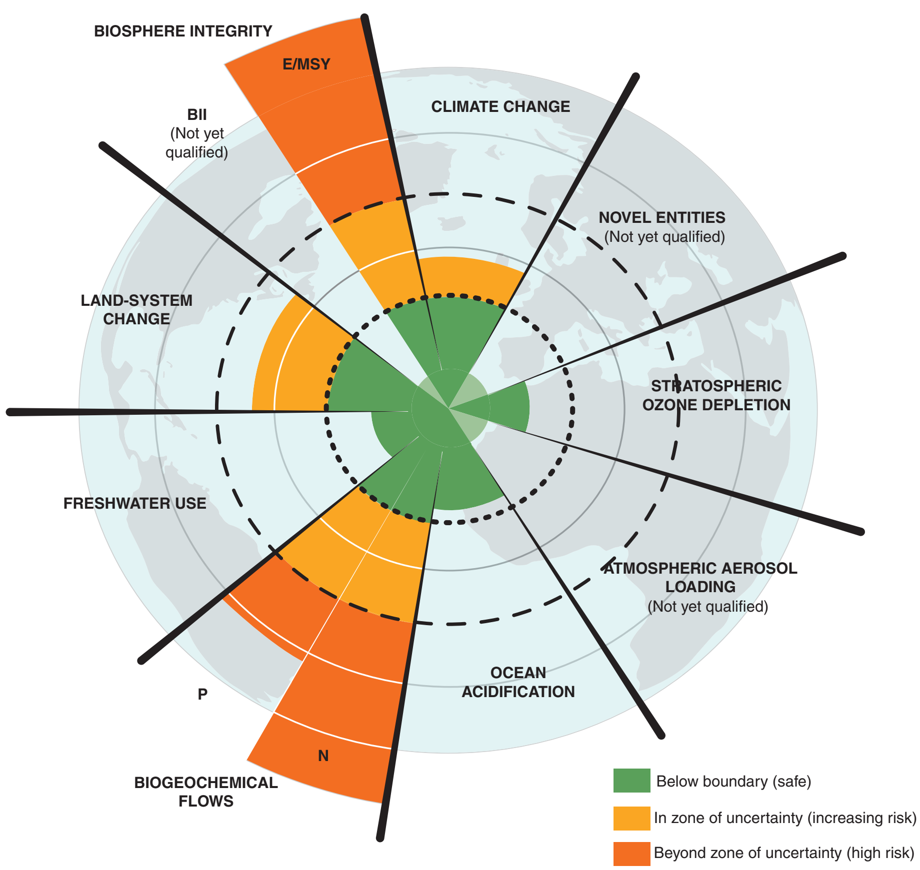
[123] We are grateful to Peter Raven for correspondence on this.

4.1.2 Safe Operating Distances from Planetary Boundaries

Further evidence of the biosphere's degradation is adduced from a study of Earth System processes. The idea has been to identify processes of the biosphere that are critical for maintaining the stable state we experienced in the Holocene. Rockström et al. (2009) identified *nine* biophysical processes that are critical for Earth System functioning. The authors' proposal was to set quantitative boundaries for each, beyond which the Earth's Holocene state would be put at further risk, making the move to the Anthropocene firmer. The authors named the markers that may be used to check whether the processes are undergoing rapid change *planetary boundaries*. A planetary boundary is not equivalent to a global threshold or tipping point. In any case, not all nine key processes are known to possess single definable thresholds, and for those where a threshold is known to exist, there are uncertainties about where they might lie. Boundaries are placed upstream of these thresholds at the safe end of the zone of uncertainty.[124]

Although not all the nine processes have single identifiable markers, crossing the boundaries increases the risk of large-scale, potentially irreversible, environmental changes. Four of the nine processes have taken the planet into regions the authors regard as outside safe operating space, meaning that there is now increasing risk of a significant change from the biosphere's conditions in the Holocene. Biosphere integrity (for which one may read 'biodiversity') and nitrogen and phosphorus cycles have exceeded their boundaries farthest. But land-use change and climate change are also outside their safe operating space (Figure 4.5).

Figure 4.5 Critical Earth System Processes and their Boundaries



Source: Lokrantz/Azote based on Steffen et al. (2015). Note: P = phosphorus; N = nitrogen; BII = Biodiversity Intactness Index and E/MSY = extinctions per million species per year.

[124] Chapter 5 constructs the necessary language for quantifying these types of uncertainty.

Unravelling the notion of biosphere integrity has proved problematic. As Figure 4.5 shows, Rockström et al. (2009) had identified it with the extinction rate of species per million per year (E/MSY). One problem with the use of this metric is that extinction rates are estimated most often for vertebrate species (only amounting to <2% of described species). Mace et al. (2014) have argued moreover that extinction rates do not reflect the genetic library of life, nor the functional diversity of ecosystems, nor the conditions and coverage of Earth's biomes. The authors' observations speak to the markers of biodiversity we explored in Chapters 2 and 3. We see below that those markers reflect ominous features of the Anthropocene. A new boundary based on the Biodiversity Intactness Index (BII) is under development, but has yet to be quantified (Steffen et al. 2015a).

A further respect in which the idea of planetary boundaries has been extended is to study sub-global boundaries. This is important because, as was noted in Chapter 2, crossing a boundary at a regional level (e.g. destruction of the Amazon rainforest) can have implications for the whole Earth System. Regional level boundaries have now been developed for biosphere integrity, biogeochemical flows, land-use systems and freshwater use.

The idea of planetary boundaries has powerful heuristic appeal and has excited the public's imagination of the processes that govern the Earth System. It may have proved to be a problematic concept, but it is a useful classification of the Earth System's biogeochemical processes.[125]

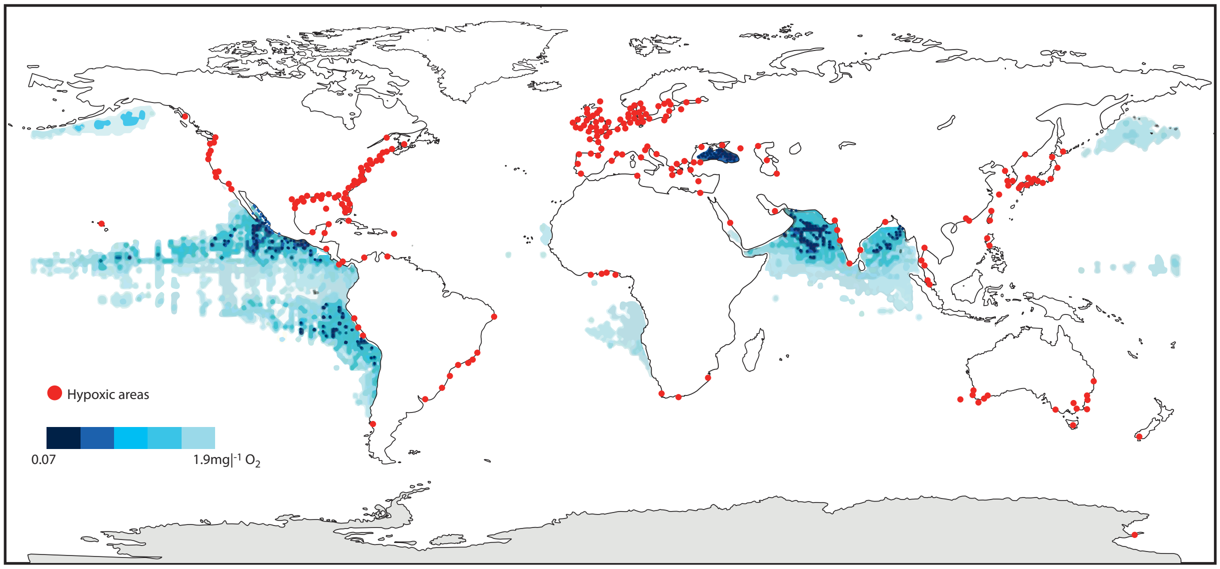
Box 4.2
Deoxidation of the Oceans

To many people today the oceans are a source of cultural services. In fact, they are an essential part of the biosphere. They help to stabilise climate, produce oxygen, nurture biodiversity, store carbon and directly support us by providing food and nutrients. The OECD estimates that by 2030 the oceans will generate US$3 trillion of goods and services annually (OECD, 2016b). By the looks of the state of the oceans today, that is an ominous forecast, for that is very likely to increase further the burdens we have inflicted on them.

Oxygen is essential for life in the oceans, but alarmingly, the levels of oxygen in our oceans have been declining dramatically over the past 50 years. While it is natural to have some low oxygen areas in our seas, the size of these areas has expanded by 4.5 million km^2 – roughly the size of the European Union – and the volume of water with zero oxygen has quadrupled. In coastal waters, the number of sites with low oxygen has risen from 50 to 500, which is probably an underestimate due to a lack of comprehensive monitoring data around the world (Figure 4.6; Breitburg et al. 2018)).

[125] Steffen et al. (2018) have further advanced the concept.

Figure 4.6 Low and Declining Oxygen Levels in Ocean and Coastal Waters



Source: Breitburg et al. (2018). *Permission to reproduce from The American Association for the Advancement of Science (AAAS).*
Note: Map created from data provided by R. Diaz, updated by members of the GO2NE network, and downloaded from the World Ocean Atlas 2009.

The reduction in oxygen in the oceans is largely due to human activities, including the global warming we are causing. Ocean warming reduces the solubility of oxygen in the water, but it also increases metabolic rates of organisms, thereby increasing oxygen consumption. This causes the water column to become more stratified, which in turn is likely to reduce the ventilation of oxygen into the ocean interior and reduce the availability of nutrients.

In coastal waters, oxygen declines are caused by increased levels of nitrogen, phosphorus and organic matter from agriculture and sewage, causing eutrophication. This increases the volume of organic matter reaching the sediments where microbial decomposition consumes oxygen. Once the oxygen levels are low the systems often do not return back to their original state.

What would happen to the biosphere if life in the oceans was to be extinguished? Here is a possible scenario:

Given that prokaryotes (bacteria, fungi) are masters of difficult environments, we could imagine they would be able to live, even thrive, in the oceans after everything else died. The biogeochemical cycles, planetary gas (for example CO_2) cycles and nutrient flows stemming from deaths in the oceans would rapidly cascade toward major, abrupt changes in ecosystems on land and in river systems; to an extent that one could reasonably envisage a steady major long-term decline in terrestrial biodiversity through extinctions. It could even be that the changes would be so enormous that life on land itself ceases for the vast majority of organismal lineages. Perhaps not total annihilation over time, but a mass extinction that has not occurred since life began.[126]

[126] We are grateful to Tim Littlewood of the Natural History Museum, London, for the scenario that is sketched.

4.1.3 Biodiversity Indicators

Erosion of natural capital usually goes unrecorded in official economic statistics because Gross Domestic Product (GDP) does not record depreciation of capital assets. Destroy biodiversity so as to build a shopping mall, and the national accounts will record the increase in produced capital (the shopping mall is an investment), but not the disinvestment in natural capital unless it commanded a market price. While industrial output increased by a multiple of 40 during the 20th century, the use of energy increased by a multiple of 16, methane-producing cattle population grew in pace with human population, fish catch increased by a multiple of 35, and carbon and sulphur dioxide emissions rose by more than 10. Human appropriation of terrestrial NPP has been variously estimated to be around 20–40%, and it is thought that over 50% are being appropriated in many of the most intensively farmed regions (Krausmann et al. 2013; Haberl, Erb and Krausmann, 2014; Williams et al. 2015). Human activity today deposits more nitrogen compounds into terrestrial and marine ecosystems than is generated in the natural nitrogen cycle (Vitousek et al. 1997). In Chapter 3, it was noted that discharges of phosphorus from agriculture into water bodies is a major ecological concern. Soil acidification, eutrophication of freshwater lakes and marine dead zones are among the consequences of nitrogen and phosphorus overload. These figures tell us much about the extent to which humanity is interfering with biogeochemical processes.

Biodiversity loss at a local level may be observable but tracking the state of the biosphere at the global level is no easy matter. Regulating and maintenance services (Chapter 2) are in any case hard to monitor. Which is why it is prudent to track biodiversity loss along as many routes as experience and evidence point to. Although the work of the Intergovernmental Panel on Climate Change (IPCC) on global climate change justifiably receives continuous global attention, the Millennium Ecosystem Assessment (MA, 2005a-d) recorded large-scale biodiversity losses in a wide range of ecosystems but has rarely been acknowledged by the public. The MA reported that 15 of the 24 ecosystems the authors had reviewed world-wide were either degraded or being exploited at unsustainable rates. The publication also reported that extraction of provisioning goods has increased, while regulating and maintenance services have declined. It also noted a decline in cultural services.

The MA noted, for example, that coastal zones account for some 20% of the Earth's surface but are inhabited by more than 45% of the world's population. An overwhelming majority of megacities are located there as well. The ecosystems in the zones include coral reefs, mangrove forests, salt marshes and other wetlands, seagrasses and seaweed beds, beaches and sand dunes, estuaries and lagoons, forests and grasslands (Turner, 2011). These ecosystems provide a range of services, including carbon, nutrient and sediment storage; water flow regulation; and quality control. They also serve as a buffer against storms and soil erosion. MA reported that over the previous three decades 50% of marshes, 35% of mangroves and 40% of reefs had been either lost or degraded.[127] In a decade-long study (2003 to 2014) that peers deeper into the state of the world's rainforests than satellite images are able to provide, Baccini et al. (2017) estimated that annually the forests captured around 435 million tonnes of carbon but lost over around 860 million tonnes, 70% of which was due to deforestation and, more generally, land degradation.

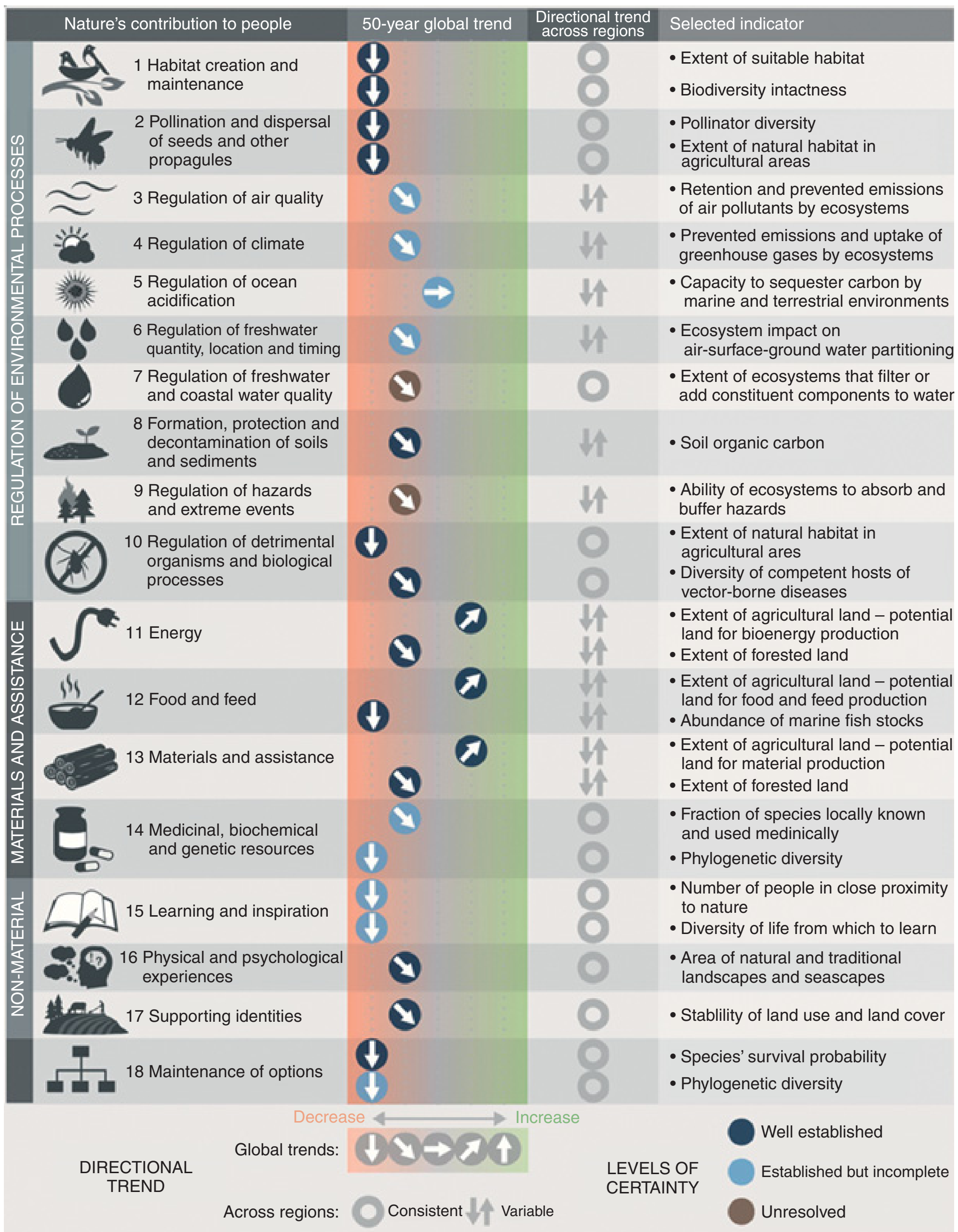
The publication by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019a) presents an extensive, spatially sensitive coverage of the biodiversity loss that is taking place today. The evidence collated there is even more disturbing than in the previous assessment by the MA. For example, since the early 1970s, there has been a decline in 14 of 18 categories of Nature's services, including purification of water, air quality, and disease regulation.[128] Reporting the

[127] See also Turner and Schaafsma (2015) for a fine collection of essays on the state of coastal ecosystems.

[128] MA (2005a-d) and IPBES (2019a) are reports on the state of the global environment. This Review should be seen as a complement to them. We allude to their findings, but do not rehearse them here in any detail. We use their findings as guides for framing the economics of biodiversity.

ongoing work on the Amazon by environmental scientists (see Lovejoy and Hannah, 2019), IPBES notes that the Amazon rainforest has shrunk by a sixth since the UN Convention on Biological Diversity was established in Rio de Janeiro in 1992. The publication also reports that the extent and condition of our ecosystems have declined by nearly 50% from their natural state and that only 23% of the land and 13% of the sea remain classified as 'wilderness'. Figure 4.7 presents the authors' findings in greater detail.

Figure 4.7 Global Trends in the Capacity of Nature to Sustain Contributions to Good Quality of Life from 1970 to the Present



Source: IPBES (2019a).

Box 4.3

Soil Biodiversity Loss

Soil erosion is usually slow in stable ecosystems but accelerates with the removal of vegetation; for example, deforestation.[129] According to a 1998 estimate, we obtain more than 99% of our food calories from land-based products, even while loss of soil organic carbon through conversion to agriculture is significant (Pimentel, 2006; Sanderman, Hengl, and Fiske, 2017).[130] Studies suggest that some 80% of the globe's farmland has moderate to severe erosion, first (surprisingly, to the uninitiated) from water and second from wind. Wetlands hold specific types of soil, rich in carbon and nutrients (as in peatlands; Box 4.7). Nearly 90% of wetlands have been lost over the past 300 years; about 35% since 1970 (IPBES, 2018). Collating data on soil erosion, WWF (2017) reported that some half of all top soils have eroded in the past 150 years. A typical estimate is that 75 billion tonnes of soil erode annually at a rate 13 to 40 times the background rates of erosion that prevailed before the acceleration caused by human dominance of the biosphere (Pimentel and Kounang, 1998). The rate of soil erosion accompanying land-use change is judged to be the highest in the past 500 million years (Wilkinson and McElroy, 2007), and some regard it to be the greatest geomorphic agent on the planet today (Hooke, 2000).

What happens when the diversity of life within soil is lost? Wagg et al. (2014) found a strong relationship between ecosystem functions and indicators of soil biodiversity. Reductions in soil biodiversity contribute to eutrophication of surface water, reduced above-ground biodiversity and global warming. Declines in soil biodiversity cause declines in performance of a number of regulating and maintenance services (Bender, Wagg and Van Der Heijden, 2016). Alarmingly, if soil biodiversity were lost completely, the land-based food system would cease to function.

Soil biodiversity loss can be identified by combining quantitative estimates of the circumstances and substances that destroy soil organisms. They include habitat fragmentation, invasive species, climate change, urban sprawl over soils, soil erosion, and soil pollution such as industrial fertilisers and pesticides. Moreover, soil degradation accelerates runoff, and erosion moves the organic sediments, rich in macronutrients, to water bodies, resulting in eutrophication and oxygen collapse in aquatic ecosystems. Dead zones, as in the Gulf of Mexico, are an example.

Once lost, can soil biodiversity be restored? Reduced soil disturbance and increased organic matter as well as the use of deeper rooting crop varieties can help improve soil health, as can cover crops, changes to crop rotations, and no-till approaches. Such practices are the substance of 'organic farming', a subject that we return to in Chapter 16.

4.1.4 Global Natural Capital Accounts

National accounting systems do not track our use of the biosphere's goods and services. GDP does not record the depreciation (nor possible appreciation) of natural capital. The evidence we have cited here so far says that while modern technology has enabled humanity in recent decades to obtain provisioning goods at an increasing rate (the Green Revolution of the 1960s and the 1970s was the defining event for that), regulating and maintenance services and cultural services have shrunk.

If we were to think of the biosphere as a stock of capital – natural capital – its net regeneration rate would be its yield per unit of time. By this reckoning, natural capital is a stock, its yield is a flow. Of course, that stock is composed of a myriad of stocks of assets, which we may call *natural resources*,

[129] The material here is based on Beach, Luzzadder-Beach and Dunning (2019).

[130] Pimentel (2006) estimated that the costs of soil erosion in the US is over US$38 billion.

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some being non-renewable (fossil fuels), while others are self-renewable with regeneration rates that can differ by orders of magnitudes (bacteria, minnows, whales, redwoods). Thus, the biosphere's yield in a period of time is not a single number, but the yields of a myriad of goods and services. Accounting for them provides the beginnings of a way to record the value of the biosphere's (net) regeneration rate. By 'value' we do not mean market value, for many forms of natural capital do not have markets at all – they are free to all who use them – and those that do reflect distorted values owing to institutional imperfections. So, by value we mean 'accounting value'.

The *accounting value* of the stock of an asset is its contribution to societal well-being; that is, it reflects the asset's social worth. The asset's *accounting price* is the accounting value of a (marginal) unit of the asset. The way natural capital accountants estimate the value of ecosystems is to estimate the accounting value of the flows of goods and services provided by ecosystems, and then estimate the corresponding accounting value of the ecosystems themselves by computing the present (discounted) value (PDV) of the flows. Chapter 13 shows how that conversion is made.

A country's *natural capital accounts* constitute a system that records the state of the economy's natural capital. The idea is to impute an accounting value to each type of natural capital and then add the values to reach the accounting value of the entire stock of natural capital to which the economy has 'claim'. The notion of claim, or the related notion of 'ownership', is the subject of Chapters 7–9.

That is all well and good in theory. In practice, estimating stocks and their accounting prices is so fraught with difficulty that the natural capital accounts that have so far been developed for sectors (e.g. Kareiva et al. 2011), national economies (e.g. Arrow et al. 2012) and the global economy (e.g. UNU-IHDP and UNEP, 2012, 2014; Managi and Kumar, 2018) are yet nowhere near as polished as the national accounts of the breakdown of the gross domestic product of national economies. Practical methods for estimating accounting prices cut through many of the problems, if only to provide simple but informative pictures of the time trajectory paths of the accounting value of natural capital, including sub-soil resources.

A decline in the accounting value of natural capital in an economy over a period of time would mean *depreciation* of natural capital. The estimates provide quantitative information on changes in the state of a country's natural capital, and are meant to be placed in parallel to estimates of changes in the value of produced capital and human capital. The aggregate value of a nation's produced capital, human capital and natural capital is called *inclusive wealth*, a concept that was introduced in Chapter 1.

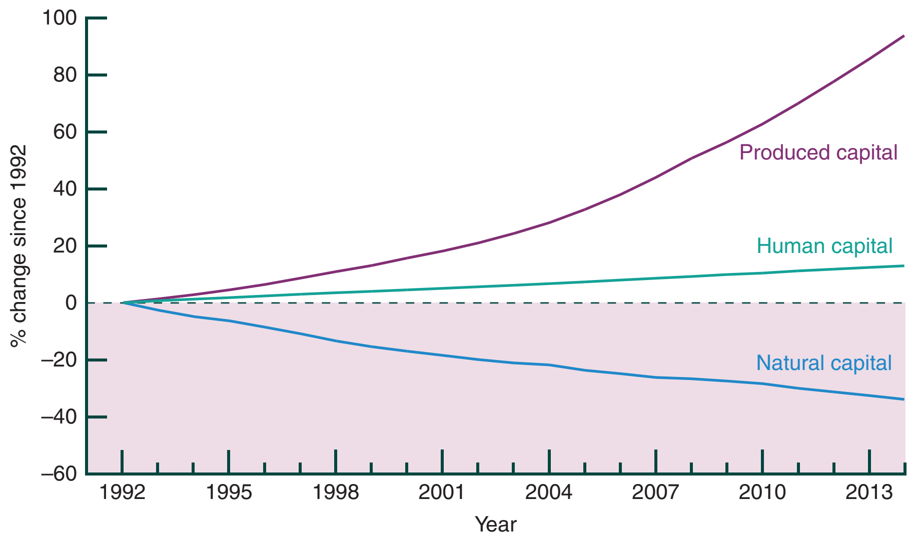
As we noted in Chapter 1, inclusive wealth taken on its own is meaningless. It is *changes* in inclusive wealth that are not only meaningful, but of enormous use to anyone wanting to understand the meaning of sustainable development. The difference between inclusive wealth in one year and in the next measures *net inclusive investment* in the country's capital goods that year. The idea of inclusive wealth and inclusive investment extends naturally to the global economy. We develop these ideas more fully in Chapter 13.

Managi and Kumar (2018) tracked the accounting values of produced capital, human capital and natural capital over the period 1992 to 2014 in 140 countries.[131] The authors built their estimates using the UN data base. In their work, renewable resources include forest resources (stocks of timber and a selected group of non-timber resources), fisheries (stocks were estimated from past records of catch), agricultural land (cropland and pastureland); while non-renewable resources cover fossil fuels and a selected set of minerals. Figures for the social cost of carbon (a negative accounting price) of greenhouse gas emissions were used to address future losses from global carbon change (see

[131] The value of produced capital (PC) was obtained from official national accounts. Data limitations meant that natural capital (NC) was limited to minerals and fossil fuels, agricultural land, forests as sources of timber, and fisheries. Market prices were used to value them. The accounting value of human capital (HC) was estimated by using the approximations in Arrow et al. (2012) for both education and health.

Chapter 10). Figure 4.8 displays the authors' estimates of global per capita accounting values of the three classes of capital goods over the period 1992 to 2014. It shows that globally produced capital per head doubled and human capital per head increased by about 13%, but the value of the stock of natural capital per head declined by nearly 40%.

Figure 4.8 Global Wealth Per Capita, 1992 to 2014



Source: Managi and Kumar (2018).

4.2 Demand and Supply

In a classic decomposition of humanity's impact on the biosphere, Ehrlich and Holdren (1971) identified global population size, individual demands on the biosphere – as reflected in, say, living standards – and the technologies and institutions in play as shaping humanity's demand for the biosphere's goods and services. We build on their analysis by decomposing the demand in quantitative terms. We first decompose the demands that are made, but by smaller economic units – from national economies to village economies in poor countries. We then sum the demands to arrive at the aggregate demand of the global economy. The decomposition of demand allows us to identify the overarching factors that determine it. It is then possible to ask what steps need to be taken in order to alter the demand. We then compare that demand with the biosphere's regeneration rate. When humanity's demand exceeds the regeneration rate, the biosphere depreciates; if it were to be less, the biosphere would appreciate. Uncovering the relationship between demand and supply is the core of the Review.[132]

4.2.1 Aggregate Demand

Humanity's demands on the biosphere per unit of time – Ehrlich and Holdren called it *impact* – is known today as the *global ecological footprint*. We begin by defining the footprint of smaller economic units and then sum them to define the global footprint. For convenience we shall use the terms 'ecological footprint' and 'human impact' interchangeably.

[132] This section is based on Barrett et al. (2020).

Let us divide the global economy into distinct economic units, labelled by i, numbered as 1, 2, . . . and so on. Depending on the context, the units are individuals (that is the relevant partition of population when sociologists study age-related consumption patterns), households (the relevant partition for national environmental policy), nations (the relevant partition in climate negotiations) or the world as a whole (the scope of this Review). Let N_i be the population size of i and y_i an index of *human activity* per person in i per unit of time. Then $N_i y_i$ is aggregate activity by members of i.

All human activity requires the biosphere's goods and services as inputs. So, we need to link y_i to the demands the average person in economic unit i makes of the biosphere. Estimating y_i poses huge measurement problems, so for tractability we suppose it corresponds to the standard of living as measured by income per capita in i. For example, if i is a household, y_i is income per head in the household; if i is a nation, y_i is GDP per capita in that country; and so on. Using income as a measure of human activity almost surely yields an underestimate of what we are after, for there are many human activities that are not captured in income as measured by economic statisticians. On occasion, national income statisticians offer estimates of the magnitude of economic transactions that are missing in gross domestic income (equivalently gross domestic product, GDP), for example, the size of the black economy, but they are too scanty to be of use here. And there are human activities that would not be covered even by those corrections. So even though we know income per capita in i is an underestimate of the activity of the average person in i, we shall use it as a proxy.

We now place our analysis on the global economy. Let N denote the global population, y per capita global GDP, and let i cover the world's population. Then

$$Ny = {}_i\Sigma N_i y_i \tag{4.1}$$

(In equation (4.1) the incomes y_i are summed over the whole world's population.) We now trace y to the biosphere's goods and services.

The demands we make of the biosphere take two forms: (1) We harvest Nature's goods and use Nature's services for consumption and production. Fish, timber and fresh water constitute goods; whereas pollination, water purification, flood protection, and carbon sequestration and storage constitute services. (2) We use the biosphere as a sink for our waste products. Landfills, rivers carrying pollutants into estuaries and carbon concentration in the atmosphere are examples of our use of the biosphere as a sink for our waste.

Let X denote what we extract or harvest from the biosphere and let Z denote the demand we make of the biosphere as a pollution sink. As both are functions of Ny, we write $X = X(Ny)$ and $Z = Z(Ny)$. The X-function records that both production and consumption require the biosphere's goods and services as inputs, while the Z-function reflects the fact that waste products are inevitably associated with production and consumption and they impose a strain on the biosphere. Partitioning our ecological footprint into X and Z reconfirms that pollution is the reverse of conservation.

Let α_X be a numerical measure of the efficiency with which the biosphere's goods and services are converted into global GDP; and let α_Z be a numerical measure of the extent to which the biosphere is transformed by global waste products (the latter in part depends on the extent to which we treat our waste before discharging them). So, we have $X = Ny/\alpha_X$ and $Z = Ny/\alpha_Z$.

Define $\alpha = (\alpha_X + \alpha_Z)/(\alpha_X\alpha_Z)$. Then $(Ny/\alpha_X + Ny/\alpha_Z) \equiv Ny/\alpha$ is our proxy measure of the global ecological footprint.[133] Writing the latter as I (Ehrlich-Holdren's 'Impact') we have

[133] As noted previously, Ehrlich and Holdren (1971) had called what is today called 'ecological footprint', 'human impact'.

$$I = (Ny/\alpha_X + Ny/\alpha_Z) \equiv Ny/\alpha \quad (4.2)$$

The distribution of global GDP affects the efficiency coefficients α_X and α_Z, but here we are concerned with global aggregates.[134] In Section 4.5, we study the distribution of ecological footprints across households, villages, regions, or other disaggregated groups of institutions. There we will replace the word 'biosphere' by the term 'ecosystem'.[135] The distribution of components of the Impact Inequality is considered further in Chapter 14.

Decoupling the global ecological footprint, Ny/α, also serves to remind us that measures to reduce environmental pollution, Z, can raise our demand for the biosphere's products (X). Solar panels require minerals such as aluminium, cadmium, and zinc. But to obtain those minerals usually requires fragmenting forests (Section 4.7 and Chapter 3).

Box 4.4
Impact of the Fast Fashion Industry

The global fast fashion industry relies on cheap manufacturing to encourage more frequent purchase. Garments are discarded well before their physical life span. This consumes large amounts of textiles (rising from 5.9 kg to 13 kg per capita between 1975 and 2018) and has significant environmental impact (Peters, Sandin and Spak, 2019; Niinimäki et al. 2020). The industry has periodically been subjected to adverse publicity, but it continues to grow. In 2019, the industry was worth around US$36 billion globally and is expected to be worth around US$38 billion in 2023 (Research and Markets, 2020). Its environmental impacts include water use, chemical pollution, carbon dioxide emissions and textile waste. It is estimated that the industry produces 8–10% of global emissions of CO_2 annually and uses over 79 trillion litres of water per year (Niinimäki et ki et al. 2020). The industry is responsible also for pollution from textile treatment and dyeing, amounting to around 20% of industrial water pollution (Kant, 2012) and is responsible for approximately 35% (190,000 tonnes per year) of oceanic microplastic pollution (United Nations Climate Change, 2018). Over 92 million tonnes of textile waste ends up in landfill or is burnt (Niinimäki et ki et al. 2020).

4.2.2 Aggregate Supply

Let G denote the accounting value of the biosphere's regenerative rate (Chapter 2). G is a function of the real accounting value of the stock of the biosphere, which we write as S. Thus $G = G(S)$. This requires a heroic (read impossible!) feat of aggregation, because the biosphere has a modular structure. Depending on the fineness of the grid with which we choose to define our spatial unit, we would need weights on biospheric material in every square on the grid, to measure the material in it and estimate the weighted sum of the material across the grid.[136]

[134] Equation (4.2) could be thought to be saying that for any given value of α, N and y are in inverse relation to each other – for instance, that if N was to double then y would have to halve if global impact Ny/α was to be held constant. Arithmetically that would be correct, but the thought could be misconstrued. The reason is that N and y are not independent of one another: we humans have not only mouths, but hands and brains too. Thus, y is a function of N. Chapter 4* presents a complete capital model from which 'trade-offs' between N and y can be estimated at various stages of economic development. Dasgupta and Dasgupta (2021) have constructed simple methods that can be deployed on the model to calculate trade-offs between N and y that are consistent with sustainable development.

[135] The decomposition of I in equation (4.2) when the impact I in question is global carbon emissions is known as the Kaya Identity. See Kaya and Yokobori (1997).

[136] For simplicity, it may help to interpret biospheric material as biomass. The relevant set of weights would then be different, of course, because biospheric processes involve interactions between non-biomass material and biomass.

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That would be S. The weights to use are the accounting prices we encountered in Section 4.1.4. Invoking the function $G(S)$ here serves only as a heuristic device for explaining humanity's overshoot in its demands on the biosphere. The function points to where policy can be directed; it is not meant for determining policy.

In Figure 3.2 and Box 3.3, we depicted the widely used, cubic form of G with a threshold L, such that if S were to cross it, the ecosystem would be a 'dead zone'. Here we go beyond the quadratic form and reconfirm its general features, such that G is a declining function of S at large values of S. The analogy is with the fishery, modelled in Box 3.3, which is bounded in extent and so has a finite carrying capacity. In the range of stocks we are concerned with here (stocks below the level capable of sustaining maximum sustainable yield), $dG/dS > 0$; that is, locally G increases if S increases. For simplicity of exposition we are assuming here that G is a deterministic function. In fact, the biosphere is governed by stochastic processes, meaning that G is a stochastic function. In Chapter 5, we show how policy can be designed in a stochastic world.

The G-function can be affected by policy. Investment in biotechnology is one general class of policies. A recent experiment in American Samoa found that transplanted heat-tolerant corals were more likely to survive a bleaching event than less tolerant local corals, enabling quicker recovery of the ecosystem after such an event – a technological intervention known as 'ecosystem engineering' (Morikawa and Palumbi, 2019). But importing foreign species into ecosystems has been known to have unintended, detrimental consequences. More familiar, still strangely controversial, interventions involve genetically modified crops, which can raise food production. In Chapter 16, we discuss sustainable food prospects, where genetically modified crops can play a vital role.

4.3 The Impact Inequality

Section 4.1 produced evidence that over several decades aggregate demand per unit of time, $Ny/\alpha_X + Ny/\alpha_Z$, has exceeded aggregate supply $G(S)$ per unit of time. That reads as

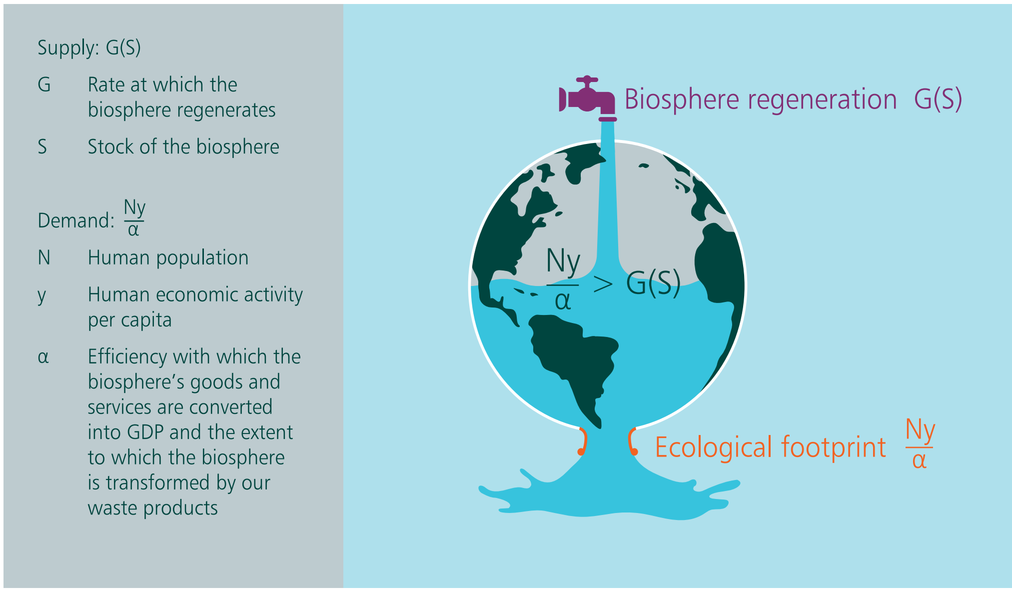
$$Ny/\alpha > G(S) \tag{4.3}$$

We call expression (4.3) the *Impact Inequality* (see also Figure 4.9).[137]

The Impact Inequality as presented in expression (4.3) applies to the biosphere as a whole. Although the notion of ecological footprint (the left-hand side of the Inequality) can be applied to any group of individuals – from the individual and the household, to nations and the global population – trade in commodities and services breaks the link between demand (Ny/α) and supply ($G(S)$) for economic units smaller than the world as a whole. The ecological footprint of a nation will not balance the regenerative rate of its ecosystems if its trade in the biosphere's goods and services does not balance, in units of biospheric material. Of course, it could be that a country pays for its imports, perhaps even at their appropriate prices, but that is a different matter. Here we are only formulating a way to break down the global imbalance of demand and supply of those goods and services into imbalances among groups in the global population; we are not discussing 'fair trade'. Trade is discussed further in Chapter 15.

[137] The Impact Inequality was formulated in this form by Barrett et al. (2020).

Figure 4.9 The Impact Inequality



Source: Described in Barrett et al. (2020).

If the global ecological footprint, *I*, exceeds the biosphere's regenerative rate, *G*, the biosphere as a stock diminishes, and the gap between *I* and *G* increases. Similarly, if the footprint is less than the biosphere's regenerative rate, the stock increases, and the gap between *I* and *G* shrinks.[138] However, either global population (*N*) or global output per capita (*y*), or both, could increase without making additional demands on the biosphere *provided* either α_X or α_Z and thus α was to increase correspondingly. Improvements in technology (e.g. substituting degradable waste for persistent pollutants; decarbonising the energy sector) and institutions and practices (e.g. establishing Protected Areas; reducing food waste), and appropriate redistributions of wealth are among the means by which α can be raised.

The factors affecting our demand for the biosphere's goods and services, namely *N*, *y*, α_X and α_Z, affect one another. When a region of the Amazon rainforest is converted into cattle ranches, the transformation would be expected to raise food production by raising the efficiency with which land is used to grow crops (a rise in the corresponding α_X), but it lowers α_Z (industrial fertilisers and pesticides degrade the soils and water bodies). The transformation could be read as reducing *S*, or alternatively, because the composition of the biome changes, it could be read as a less productive *G*-function. The overall effect would be to widen the gap between *G*(*S*) and $(Ny/\alpha_X + Ny/\alpha_Z)$.

In an ingenious set of exercises, Wackernagel and Beyers (2019) have estimated *G* by calculating the area of land and sea surface covering different categories of ecosystems (agricultural land, plantations, wetlands, fisheries, marshes, oceans, forests, and so on) that is needed, given existing technologies, to meet humanity's current demands for various provisioning goods, while leaving space to allow for other life forms to provide pollination, seed dispersal, fertilization, and decomposition of waste. Thus, the land-sea area required to meet our demand for natural fibres on a sustainable basis is taken to be Earth's bio-capacity for that demand. And so on for our other demands. However, ecosystems differ in their ability to provide the same service. For example, marshes sequester 10 times the carbon temperate forests do. A sq. m of marshland is therefore awarded a weight 10 as against 1 for a sq. m of a temperate forest, and

[138] Bifurcations leading to regime shifts and irreversibilities do not affect the formulation. Crossing a bifurcation amounts to a discontinuous change in the biosphere's regenerative rate.

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so on. The authors obtain *G* by estimating the weighted sum of the areas required. Using that apparatus, they calculate that the ratio of the left-hand side to the right-hand side in expression (4.3) is currently about 1.7, whence the metaphor that we need 1.7 Earths to meet humanity's current demands from it. Whatever the term 'sustainable development' could mean, it must as a minimum mean transforming the Impact Inequality into an equality; that is, reducing our overreach of the biosphere to zero. (Net-zero emissions is the corresponding idea when restricted to the Earth system as a sink for our carbon emissions.)

Box 4.5
The Idea of Indefinite Economic Growth

The literature on the economics of climate change has mostly taken future projections of *Ny* as given and has focused instead on raising the efficiency parameters α_X and α_Z by decarbonising the economy and removing CO_2 from the atmosphere, and by raising the *G*-function by geo-engineering. Why then have α_X, α_Z, and the *G*-function not risen more to close the gap between carbon emissions and the biosphere's capacity for assimilating carbon? The reasons are low rates of innovation and investment in non-fossil fuel energy sources, carbon capture and carbon storage technologies. Those low rates, in turn, have been due to persistent and pervasive institutional failure to achieve global collective action in limiting climate change. Despite nearly 30 years of diplomatic effort, the world has been unable to overturn the tragedy of the climate commons.[139]

But the reason carbon concentration in the atmosphere has increased is not only that de-carbonisation and direct carbon removal have been slow, it is also that growth in both global GDP per capita (*y*) and world population (*N*) have been strong. Ironically, publications on the economics of climate change and international negotiations over carbon emissions have not only *not* questioned the desirability of continual global economic growth, they would appear to have taken as given that it is the only viable route for (i) reducing carbon emissions, (ii) eliminating global poverty, and more generally (iii) ensuring that development is sustainable. That has been the implicit assumption underlying the UN's SDGs.

That stance has given rise to a paradox: *growth in global output (Ny) is seen as necessary for providing the funds that will be needed for reducing our ecological footprint (Ny/α), even though growth in global output is known to increase the footprint*.

In the chapters that follow, we move away from the viewpoint that has given rise to the paradox. The viewpoint is built on the thought that humanity is *external* to the natural world. It sees us as dipping into the biosphere for its goods and services, transforming them for our production and consumption, and then discharging the residue into the biosphere as waste. The Review is in contrast built on a recognition that humanity is *embedded* in the natural world. It will be shown that this somewhat metaphysical distinction – being 'external to' and being 'embedded in' – has enormous implications for our conception of future economic possibilities. The conception we adopt here says that *Ny* cannot be increased indefinitely: it is instead *bounded* (Chapter 4*).

4.4 Two Notions of Inequality

The decomposition of Impact into *N*, *y*, and α has been expressed in aggregate terms. Quite obviously, it is decomposable into income groups. Let *i*, *j*, variously denote households. Households differ according to their incomes, y_i, y_j, and so on, but they differ as well with regard to the efficiency with which they convert the biosphere's goods and services into income. It is conventional to view inequality in terms of

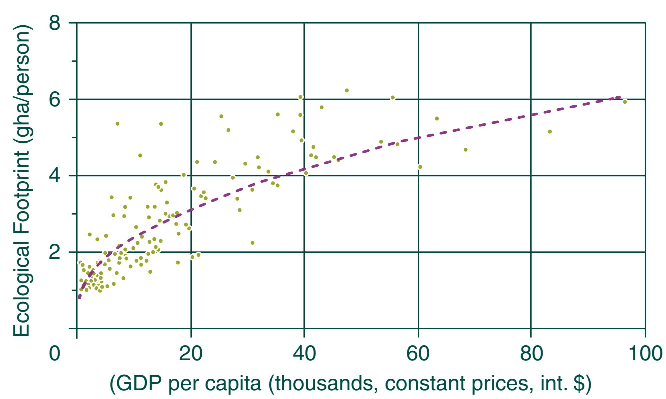
[139] In a sustained research programme, Scott Barrett has explored reasons for the failure of climate negotiations and has proposed treaty architectures that would encourage compliance. See Barrett (2003, 2012, 2015) and Aldy, Barrett, and Stavins (2003).

the distribution of household incomes, but in the Review we are interested also in inequality among households in terms of the impact they have on the biosphere. The latter is reflected in the distribution of incomes when corrected for the efficiency with which the biosphere's goods and services are converted into income (i.e. y_i/α_i). And income and income in efficiency units are not the same. We may read y_i/α_i as household *i*'s ecological footprint.[140]

Imagine that you label households by income and rank them in terms of increasing income. In an economy with N households, we then have $y_i < y_{i+1}$ for $i = 1, \ldots, N$. The IPCC (2014) reported from cross-national statistics that carbon emissions are an increasing function of income. There is a corresponding finding that says ecological footprint is an increasing function of income (IPBES, 2019a; Wackernagel et al. 2019). So we assume that $y_i/\alpha_i < y_{i+1}/\alpha_{i+1}$, for all i. In this reading, households enjoying higher income demand more from the biosphere.

A question arises whether the curve y_i/α_i is convex or concave. Consider an income interval where the function is convex. An egalitarian redistribution of incomes among households in that interval would lead to a smaller global ecological footprint, implying there is no conflict between income equality and the biosphere's integrity. But in a concave interval, the reverse holds: *egalitarian redistributions of incomes would lead to larger global ecological footprints and society would face a cruel choice between income equality and the biosphere's integrity* (A. Dasgupta and Dasgupta, 2017).[141] Figure 4.10, which displays a regression between the ecological footprint of nations and GDP per capita, shows that our demand for the biosphere's goods and services increases with affluence and development but that the efficiency with which we transform them so increases with affluence that ecological footprint is a concave function of income at all levels of incomes. In short, ecological footprint rises less than proportionately with income. That suggests, ominously, that egalitarian redistributions of incomes lead to larger global ecological footprints, other things the same.[142] Distribution is discussed further in Chapter 14.

Figure 4.10 Ecological Footprint and Income



Source: World Bank (2020a), Global Footprint Network (2019), and Review calculations.

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[140] For notational simplicity we integrate extraction and pollution and speak of a single efficiency index, α.

[141] The modern classics on the meaning of egalitarian income redistributions are Kolm (1969) and Atkinson (1970). We avoid details here, but readers should note that Figure 4.10 (below in the text) says the global ecological footprint would be higher than it is today if everyone in the world was to receive an equal share of today's global income.

[142] Figure 4.10 combines data from the World Bank on per capita GDP of nations and estimates from the Global Footprint Network on ecological footprint per capita (in global hectares). A total of 136 countries are in the sample, including both developed and developing countries. Reinterpreting the Impact Inequality, if I denotes ecological footprint and y is income per capita, the estimated functional form is $I = 0.97y^{0.41}$, with $R^2 = 0.71$.

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4.5 The Impact Equation

Over the long run, global demand (per unit of time) must equal the biosphere's ability to meet that supply (per unit of time) on a *sustainable* basis. The widely discussed UN SDGs were formulated on the assumption that they can be attained, but the background documents did not probe the question of whether they are sustainable in a global economy that simultaneously enjoys growth in global GDP.

The economics of biodiversity involves a dynamic resource allocation problem (Chapter 4* and Chapter 13*). The demand we make on the biosphere per unit of time does not have to equal the biosphere's ability to supply goods and services per unit of time, because the difference is naturally accommodated by a change in the biosphere's stock *S*. A world rich in healthy ecosystems could, on utilitarian grounds, choose to draw down the biosphere and use the goods and services it supplies so as to accumulate produced capital and human capital. That is what economic development has come to mean among many thinkers, but the scenario comes in tandem with an overshoot in our demands from the biosphere. The overshoot cannot be maintained indefinitely because our life support system would be threatened.

We therefore work backwards, by first identifying a condition the global economy's treatment of the biosphere must satisfy if the SDGs are themselves to be sustainable. That condition tells us to find ways in which *S* can be stabilised. To *sustain* that stabilised value of *S* requires that the global ecological footprint equals the biosphere's regenerative rate, that is,

$$Ny/\alpha_X + Ny/\alpha_Z \equiv Ny/\alpha = G(S) \qquad (4.4)$$

Equation (4.4), which we call the Impact Equation, applies to the biosphere as a whole.

The Impact Equation is a condition of *global sustainability*. The equation does not say what *S* should be. There is an entire range of values of *S* and corresponding sets of values of the remaining factors, N, y, α_X, α_Z, and the parameters of the *G*-function for which equation (4.4) can be expected to hold. The requirement that a state of affairs is *sustainable* is that it can persist indefinitely. That is different from a requirement we may insist on, that the state of affairs we should aim for should in addition be *desirable*. This distinction will be studied in Chapters 11–13.[143]

Suppose then that we have identified the most desirable value of *S*, say *S**, which is the state of the biosphere the global economy should aim for. The problem remains that there are potentially an infinite number of paths that would lead the biosphere from today's *S* to the target level *S**. And that is a dynamic portfolio management problem (Chapter 1). Therefore the most desirable way for getting from where we are today to where we ought to be must at each moment satisfy arbitrage conditions among all assets (produced, human and natural), and they must also include a set of arbitrage conditions that mediate between the present generation's well-being and the well-being of future generations (Chapter 10). In Chapter 13, we show that these arbitrage conditions would be satisfied if the allocation of assets toward different activities and engagements were to be governed by the rule that an inclusive measure of *wealth* should be maximised. Optimal portfolio management for an economy, be it a national economy or the global economy, involves wealth maximisation at each moment. The implication is striking: *economic progress should be read as growth in inclusive wealth, not growth in GDP nor growth in any of the other ad hoc measures that have been proposed in recent years such as the UN's Human Development Index*.

[143] Equation (B3.2.1) in Box 3.3 showed that in a fishery that exhibits a threshold *A*, any biomass *S* in the interval (*A*,*K*) is sustainable, so long as annual rate of harvest demand *R* equals the fishery's regenerative rate *G*(*S*).

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Box 4.6
Reaching the UN SDGs

The Impact Inequality offers a way to discover the policies and behavioural changes that will be required if the global economy is to achieve the UN SDGs. To illustrate, we consider the Goals related to reaching a sustainable use of the environment by year 2030.

We have defined the global ecological footprint by Ny/α. The Global Footprint Network (GFN) in contrast defines it as the ratio of the global demand for the biosphere's goods and services and the biosphere's current capacity to supply them on a sustainable basis (which we interpret here as G). The GFN's global ecological footprint is then $[Ny/\alpha]/G$. Wackernagel and Beyers (2019) report that the ratio increased from 1 in 1970 to 1.7 in 2019. That means the ratio increased at an average annual rate of 1.1%.[144] Moreover, global GDP at constant prices has increased since 1970 at an average annual rate of 3.4%.

We turn to the right-hand side of the Impact Inequality. As noted previously, Managi and Kumar (2018) estimated that the value of per capita global natural capital declined by 40% between 1992 and 2014. That converts to an annual percentage rate of decline of 2.3%. But world population grew approximately at 1.1% in that period. Taken together it follows that the value of global natural capital declined at an annual rate of 1.2%. Because there are no estimates of the form of the G-function, we assume for simplicity that local variation is a good approximation, meaning that G is proportional to S. So, G can also be taken to have declined at an annual rate of 1.2%.[145]

The estimates for the annual percentage rates of change of Ny, G, and $[Ny/\alpha]/G$ enable us to calculate that α had been increasing at an annual percentage rate of 3.5% in the period 1992 to 2014. Suppose we want to reach Impact Equality in year 2030. That would require $[Ny/\alpha]/G$ to shrink from its current value of 1.7 to 1 in 10 years' time, implying that it must decline at an average annual rate of 5.4%. Assuming global GDP continues to grow at 3.4% annually and G continues to decline at 1.2% (i.e. business is assumed to continue as usual), how fast must α rise?

To calculate that, let us write as $g(X)$ the percentage rate of change of any variable X. We then have

$$g([Ny/\alpha]/G) = g(Ny) - g(\alpha) - g(G) \qquad \text{(B4.6.1)}$$

Equation (B4.6.1) can be re-arranged as

$$g(\alpha) = g(Ny) - g([Ny/\alpha]/G) - g(G) \qquad \text{(B4.6.2)}$$

We now place the estimates of the terms on the right-hand side of equation (B4.6.2) to obtain

$$g(\alpha) = 0.034 + 0.054 + 0.012 = 0.1$$

In short, α must increase at an annual rate of 10.0%. As that is a huge hike from the historical rate of 3.5%, we consider a different scenario.

[144] GFN's estimates are based on data furnished by the United Nations Statistical Office. For an account of the methods that are deployed for estimating G, see Wackernagel and Beyers (2019). It should be noted that as an approximation they take G to be linear in S.

[145] While Managi and Kumar (2018) base their work on the UN data base, the questions they ask differ from the questions asked by the GFN (Wackernagel and Beyers, 2019). Moreover, because the Managi-Kumar study includes fossil fuels and minerals, we must assume for our purposes of illustration that the percentage rate of global decline in the accounting value of sub-soil resources equalled the corresponding figure for ecological resources. Using data from different systems of measurement in the numerical calculation we conduct here is a price we have to pay for continual neglect of the economics of biodiversity in international organisations. GDP estimates have been refined continually over the decades by thousands of experts, whereas the human footprint on the biosphere remains of interest only to a handful of people.

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Suppose global output was to remain constant from now to year 2030 and draconian steps were taken by us over our demands to limit the rate of deterioration of the biosphere to an annual 0.1%. What would be required rate of increase in α need to be? Using equation (B4.6.2) we have

$$g(\alpha) = 0.054 + 0.001 = 5.5\%$$

Even that is considerably larger than the 3.5% rate at which α has been increasing in recent decades.

4.6 Technology and Institutions

The expression $(Ny/\alpha_X + Ny/\alpha_Z)$ is the global ecological footprint in absolute terms. As noted earlier, the Global Footprint Network (Wackernagel and Beyers, 2019) defines the footprint instead as the ratio of the demand to supply; that is, $(Ny/\alpha_X + Ny/\alpha_Z)/G(S)$. The network's latest estimate (2020) is 1.6, which they read as a demand that can only be satisfied on a sustainable basis by, as a minimum, 1.6 Earths (Lin et al. 2020).[146] The estimate is very rough, but the point should not be to focus on the exact estimate. What should be uncontroversial is that $(Ny/\alpha_X + Ny/\alpha_Z)$ has exceeded $G(S)$ since the 1970s.

In subsequent chapters, we study ways in which the trajectories of y and N can be altered (see in particular Chapters 9 and 16). Here we consider a few ways by which α_X and α_Z could be raised so as to close the gap between $(Ny/\alpha_X + Ny/\alpha_Z)$ and $(G(S))$. The twin pillars of technology and institutions would be involved, for together they determine α_X and α_Z.

That institutions and technology influence one another is a commonplace assertion. Institutions are the seat of incentives, and incentives shape the production, dissemination and use of knowledge. A state that invests vigorously in life-saving technology and then applies it is able to transform society for the better. Likewise, technological possibilities shape institutions. Advances in mapping the geographical spread of natural capital and in methods to monitor its use can help enforce property rights. History is rife with examples where institutions and technology have influenced one another beneficially.

That each can be made at least partially to mitigate the other's failure is also widely recognised. While it is widely recognised that degradation of the biosphere is a manifestation of institutional failure, hope is often expressed that progress in science and technology can put things right. The economics of climate change has encouraged that thought. Development of cheap renewable energy sources would help to reduce carbon emissions to the point where carbon concentrations are kept within acceptable levels.

Nature saving technology, for example, substituting degradable waste for persistent pollutants and decarbonising the energy sector, is one class of ways in which technology can raise the aggregate efficiency index α. Institutional changes, such as improving the character and enforcement of property rights to natural resources points to another class of ways in which α can be raised. Directives that establish Protected Areas to conserve natural habitats; imposition of pollution taxes; and removal of subsidies on resource extraction and agricultural production make up another class of institutional changes that can be brought about by public policy.

Changes in behavioural norms, such as those that lead to a reduction in food waste, is yet another avenue. The incentives entrepreneurs have for developing technology are shaped by the systems of property rights in place. Remarkable post-war developments in sonar technology and advances in the technology for harvesting fish came about in large measure because ocean fisheries beyond national

[146] This is down from 1.7 in 2019 due to the impacts of the COVID-19 pandemic.

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jurisdiction are free. Unbridled application of modern technology in clearing tropical rainforests has been made possible because governments have permitted it at a small price. Both forms of environmental destruction would have been avoided had institutions not failed. There is nothing good or bad about technology per se, it is the use to which it is put that affects α. Indeed, a wealth of examples of technologies that can be a force for sustainability in the food sector are given in Chapter 16. But no matter how effectively institutions are established to synergise with technological advances, unending growth in global output is an ecological impossibility. The biosphere is bounded and there are theoretical bounds on global output. Or so we argue in Section 4.7 and Chapter 4*.

Decoupling the demand humanity makes on the biosphere into *X* and *Z* in the left-hand side of equation (4.2) also serves to remind us that measures to reduce environmental pollution (Z) can raise our demand for the biosphere's goods and services (*X*). As noted already, solar panels offer a technology for reducing carbon emissions, but solar panels are built on aluminium, zinc, cadmium, and other minerals. And mining and quarrying usually require that forests be destroyed. Equation (4.2) also reminds us that the two sides are not independent of one another. A move away from intensive farming to methods that rely on mulch, among other practices, gives rise changes in α_X and α_Z (the latter parameter would increase) in food production, but it also leads to a change in the *G*-function.

In Chapter 8, we argue that effective institutional structures are *polycentric*.[147] The most well-known among such structures is a system of markets for private goods and services, in which a central authority supplies public goods and services, including measures that brings about a fair distribution of assets among people. The price system is the hallmark of markets. It serves not only to coordinate the choices people make, it simultaneously aggregates diffused information across the economy.[148] That system however cannot serve adequately in humanity's engagement with the biosphere, because Nature's processes do not satisfy the technical conditions on production possibilities that are required for markets to function well. Three conditions are especially pertinent:

(1) Because Nature is mobile, much of the biosphere consists of 'fugitive resources', meaning that it is impossible to establish property rights to them (Chapters 7 and 8). By property rights we mean not only private rights, but also group rights including those of communities and nations.

(2) Production and consumption possibilities involving the biosphere (in other words, *all* production and consumption possibilities!) are characterised by non-linearities (Chapters 3), a condition that is at odds with a requirement of any well-functioning market system (Chapter 7).[149]

(3) The risks to life and property that are associated with ecological degradation are *positively correlated* across people (Chapter 5). That means insurance premia cannot be set at fair odds by private firms. Insurance markets are inevitably imperfect, and national and supra-national institution are needed to fill the gap. Nature-related financial risks are covered further in Chapter 17.

In later chapters of this Review we study the character of institutions that can in principle implement the Impact Equation. We will discover that the polycentric structure requires *layered* institutions: global, regional, national and communitarian. Each layer however requires an authority at the apex to achieve coordination below.

[147] Ostrom (2010a,b) popularised the term.

[148] Stiglitz (1989) is an outstanding exposition of the place of the price system in a well-functioning economy.

[149] Debreu (1959) is the classic exposition of the theory of well-functioning market economies.

Box 4.7

Reducing the Impact Inequality by Restoring the Peatlands

Peatlands comprise peat soil and the wetlands that grow on its surface. Year-round waterlogged conditions slow the process of plant decomposition to such an extent that dead plants accumulate to form peat soil, which can be several metres thick. Peatland exists in almost every country in the world and covers around 3% of global land surface (>3 million km^2) (Joosten, 2010). Appearing in such diverse forms as open, treeless vegetation in Scotland and swamp forests in South Asia and the Congo Basin, peatlands together comprise the largest natural terrestrial store of carbon, harbouring more than 450 gigatonnes of carbon, which is more than 40% of all soil carbon (Joosten, 2010). Peatlands sequester nearly 0.4 billion tons of CO_2 annually, while regulating water flow and quality, lowering the risks of flooding and the effects of droughts, preventing sea-water intrusion, and offering habitat for numerous forms of wildlife. Local inhabitants harvest their peatland so as to grow and obtain food, fibre and other local products.

Unfortunately, some 15% of the world's peatlands (i.e. about 0.4% of global land surface) has been drained for intensive cultivation, animal husbandry and human habitation (Joosten, 2010). CO_2 emissions from drained peatland now contribute more than 5% of global anthropogenic greenhouse emissions, never mind the loss of biodiversity and the corresponding loss of a multitude of ecosystem services.

The UK's peatlands, covering 12% of the nation's land area, have been in the making for over 10,000 years (ONS, 2019). Today they are in a damaged state. Acid rains and more general pollution, overgrazing and burning, draining, and drying of the peatlands for our other demands have so affected the state of the peatlands that some are emitters of carbon rather than stores.

Peat restoration, especially in the UK hills, is now a tried and tested technique. It involves blocking drains and holding water in the hills. They represent ecological solutions to restoration problems. Peat restoration projects in the Peak District's 'Moors for the Future', and two lowland restoration projects (the National Trust's 'Fen Vision' and the Wildlife Trust's 'Great Fen Project') are now yielding promising results. A case study of the use of natural capital accounting is provided in Chapter 13.

Conservationists have speculated on an even wider set of policies for peat restoration. Imagine that intensive farming in the nation's peatlands was to be abandoned and farmers were deployed to act as stewards of the wetlands. The move would in principle make no dent on Ny (FAO estimates that approximately a third of food is wasted globally[150]), but it would raise α_X and α_Z and S, thus reducing the gap between $G(S)$ and $(Ny/\alpha_X + Ny/\alpha_Z)$.

Natural England (2010) has found that under mid-range assumptions on the social cost of carbon in the atmosphere (around US$40 per ton of CO_2), restoring the nation's peatlands would be a financially effective method of reducing greenhouse gas emissions. And that estimate is based on valuing peatlands solely as carbon stores. If we were to add the other services provided by peatlands, the case for restoration increases substantially. These considerations have prompted environmentalists to suggest that the nation's peatlands be restored in their entirety by retiring agriculture from them.

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[150] This is a rough estimate due to lack of information at some stages of production, discussed in FAO (2019).

4.7 Ecosystem Complementarities and the Bounded Global Economy

Within bounds the biosphere is a self-regenerative asset, supplying us with a bewildering variety of services. In Ch. 2 (Sec. 2.4) a distinction was drawn between Nature's 'provisioning goods' and her 'regulating and maintenance services.' The former category includes food, water, timber, fibres, pharmaceuticals, and non-living material, which we transform into consumption and investment and record the transformation at the national level as GDP. The latter category, it will be remembered, includes among many other services, climate regulation, decomposition of waste, disease regulation, nutrient recycling, nitrogen fixation, air and water purification, soil regeneration, and pollination.

The evidence we have brought together in this chapter has shown that humanity has increasingly drawn on Nature's regulating and maintenance services to provide ourselves with provisioning goods. We have done that by mining ecosystems and transforming the landscape (land-use change, as it is called generically). The worldwide conversion of grasslands and forests (ecosystems with rich biodiversity) into farms, ranches, and plantations (assets with poor biodiversity) is an example. There is thus a tension between our desire for provisioning goods on the one hand and our need for regulating and maintenance services on the other. But regulating and maintenance services are fundamental, for without them there would be no provisioning goods, nor for that matter cultural services. Which is why the tension in question expresses itself today in our overshoot in demand for Nature's provisioning goods relative to her ability meet that demand on a sustainable basis (i.e., the Impact Inequality). Put another way, when we speak of a shrinking biosphere, we mean a decline in Nature's ability to supply regulating and maintenance services, caused by our ever-increasing demand for provisioning goods.

And here is another sobering finding: the processes governing the biosphere's ability to provide regulating and maintenance services are *complementary* to one another, meaning that if you draw down one such service (e.g., climate regulation) sufficiently, you will in due course draw down Nature's capacity to supply the others (e.g., as reflected in biodiversity). Nature is, to be sure, resilient – it has, after all, evolved over 4.5 billion years – but we humans today are so powerful, that we could if we put our mind to it, bring it down like a house of cards. Recent concerns over global climate change and biodiversity loss are an acknowledgement of that possibility.

The force of complementarities becomes evident when we study the components of objects that are indivisible. A steering wheel, for example, is of little use on its own, brake pads are of no use on their own, a gear appliance taken alone serves no purpose, and so on; but together they can be assembled to manufacture an automobile. Repair shops carry inventories of automobile parts, but that simply re-enforces the point that automobiles are indivisible capital goods. A car with worn out brake pads is not roadworthy. They have to be replaced.

The components of indivisible object are *perfect* complements. Complementarities among ecosystem services are not perfect, but they are far from being substitutes. In that less rigid sense, complementarities are an essential feature of the Earth System also at levels of aggregation higher than ecosystems. Within bounds the biosphere is a self-regulating entity. The bounds are defined by its stability regimes. Regulating and maintenance services, for example, are provided by the biosphere as *joint products*. Weaken any one sufficiently by overuse, and the biosphere would flip into a different stability regime.

Our ecological footprint is not only of the material we take from the biosphere, but also the transformed material we deposit into it; what is requisitioned for human use has to be returned. The macroeconomic models of growth and development in use in finance ministries and planning commissions, however, do not acknowledge that material must balance – from source to sink. Persistent pollutants such as plastics, nylon (fishing nets and synthetic textiles), toxic chemicals and metals provide examples of waste that have adverse consequences for the soils and water bodies especially. But even (perhaps, especially) biodegradable waste has to be accounted for. It does not do to imagine that if waste is biodegradable it leaves no footprint. If we overload Nature with such waste, the process of decomposition compromises other biospheric services. Pharmaceuticals such as antibiotics and fashion products such as cosmetics contaminate the soils and water bodies. They have an adverse effect on the food we eat, the water we drink, and the air we breathe. Chemical fertilisers and waste from livestock emerge at the other end of farms as waste, causing nutrient overload in streams and water bodies, disrupting the nitrogen cycle. Even the carbon dioxide emitted by our economies is a biodegradable waste: it is absorbed by primary producers for photosynthesis. But an overload compromises the ability of the biosphere to regulate climate. Global climate change will increasingly be a major cause of biodiversity loss (Lovejoy and Hannah, 2019). That will compromise the functional integrity of ecosystems. Rising concentration of carbon in the atmosphere is thus expected to bring about a chain of events that will radically alter the biosphere's workings. Regulating and maintenance services will move out of the bounds within which our economies have evolved. That is an expression of biospheric complementarities.

Those complementarities find expression in the growth of all forms of waste. It may not be possible yet to predict how that will in time affect biospheric services (Box 4.2) but what one can anticipate with a level of certainty is that the transformations will be adverse to the human economy because we did not evolve under them. If the mass of waste material continues to increase, the composition of the biota can be expected to undergo sufficient change to bring about biospheric regime shifts. No such shift could be expected to bring good news to us, for human activities evolved only under gradual changes in the biosphere's operations.

Biospheric complementarities point to a further truth: *The efficiency with which its goods and services can be converted into produced goods and services is bounded*. Formally, α is bounded (Equation (4.2)). As the biosphere's regenerative rate G is also bounded, global output is also bounded (the Impact Equality). That is the sense in which humanity is embedded in Nature.

That G is bounded finds vivid expression in the idea of *planetary boundaries* (Rockström et al. 2009; Section 4.1.1). Contemporary models of macroeconomic growth and development do not necessarily overlook the fact that Earth is bounded, what they explore instead are production possibilities in which, by exercising sufficient ingenuity (read technological progress), humanity will be able to free itself from the biosphere's constraints.

The increasing share of non-material goods in the GDP of high income countries is often cited as a move in that direction, miniaturisation in the production and use of information technology being a concrete example. One problem with the example is that the miniatures themselves are built with material goods; another is that the income drawn from a rising GDP can be, and is, spent on material goods. Currently global raw material consumption is estimated to be 90 gigatonnes a year (OECD, 2019c).[151] Mining and quarrying operations degrade ecosystems. Applying methods similar to ones deployed for estimating our global ecological footprint (Section 4.2), 50 billion tonnes a year is reckoned to be a sustainable rate. The OECD (2019c) has estimated that if the global population N in 2060 was to rise to 10 billion and per capita global income y was to rise to today's per capita income in OECD countries, raw material consumption would be about 180 billion tonnes a year. That's nearly four times the sustainable rate. Even if the idea of a weightless economy was to be believed, it would provide no solace if the biosphere was to flip to an uninhabitable state before it could be realised. We return to this issue in Chapter 9 in connection with population growth.

Contemporary models of macroeconomic growth may be interpreted as saying that the boundedness of the biosphere does not imply that the human economy has to be bounded. The existence of planetary boundaries would not necessarily preclude the possibility of perpetual economic growth, for we may feel we are entitled to imagine that with sufficient ingenuity humanity would be able to convert the

[151] The bulk of raw material consumption under the OECD's classification consists of sand, gravel and crushed rock, and metals. Timber is relatively small portion in weightage.

biosphere's goods and services into final products at an unbounded rate, that is, that there are no theoretical bounds on α. So, we need a further argument.

It is significant that a mechanical engine that converts heat into work at 100% efficiency is a theoretical impossibility. The biological counterpart is that it would not be possible even theoretically to convert our further waste into a state that makes no further demands on the assimilative services of the biosphere; for if we were able to do that, we would be able to break free of Nature. Chapter 4* presents a model of production possibilities for the global economy in which that dependence on the biosphere is represented by the idea that no matter how ingenious we are able to be, we cannot increase α to infinity (Figure 4.11).

Figure 4.11 The Economy is Embedded in the Biosphere

Box 4.8
Land-Use Change and the Spread of Viruses

It is customary to regard trade in goods as ways that smooth local disruptions across space and time. Globalisation is also applauded because it expands output and has been shown to have helped to reduce global poverty. But because globalisation has taken place when much of the biosphere is not merely free for all to use as we like but is also subsidised for our use (Annex 8.1, Chapter 8), it has increased the likelihood of societal crashes. It has done that by connecting economic units closely to one another via firms' supply chains and the movement of people. Close connections among its parts make the global economy less modular (Chapter 2): a crash in one part spreads to other parts.

There are further drivers of societal crashes. Our remarkable ability to enter every ecological niche has raised the chances of pandemics (Daily and Ehrlich, 1996; Jones et al. 2008). Humans now enter niches occupied by organisms with which we have not evolved. Intimate associations between humans and wildlife disease reservoirs have raised the risks of exposure to zoonotic viruses. Being unfamiliar pathogens, they are able to spread rapidly across the globe (Gottdenker et al. 2014).

Moreover, biodiversity loss creates niches for pathogens that are lying in wait in small numbers to explode in their populations, and for new pathogens to evolve.[152]

Enormous changes in land-use have taken place in recent history. Increases in logging and forest clearance for mining and extracting oil, cultivating oil palm and farming cattle and crops have come allied to increases in the volume of trade in bushmeat and exotic pets. These activities have disrupted vegetation and wildlife that are host to countless species of viruses and bacteria, mostly unknown so far, and also increase the number of available host species of diseases (Gibb et al. 2020). Those microbes, once released, can infect new hosts, such as humans and cattle (Jones et al. 2013). The spillovers are then transmitted via globalisation. An example is the human immunodeficiency virus, which would appear to have spread from chimpanzees and gorillas, who were being slaughtered for bushmeat in West Africa. By conservative estimates, some 33 million deaths have occurred due to the virus (UNAIDS, 2020).

Quantitative studies of the transmission of infectious diseases (e.g. Anderson and May, 1991) point to the analogous fact that wide-scale movements of people and goods make the socio-ecological world brittle in many ways. The questions epidemiologists therefore ask about the spread of an infectious disease include: Can the infection be stably maintained? Is it endemic or epidemic? What is the time course of the proportions of a population that are (i) susceptible, (ii) infected and (iii) recovered?

Mathematical models of the dynamics of infectious diseases in a host population (and the models are necessarily mathematical) in effect are the dynamics of the three categories of subjects in the host population.[153] Today the elaborate models that routinely incorporate new data to revise the values of parameters and measures of human behaviour are becoming familiar, at least several steps removed, to us all as we listen to daily reports on the spread of COVID-19 by some of the most distinguished epidemiologists of our time. But the underlying logic in the models is the three-way partitioning of a host population.[154]

Dobson et al. (2020) have made a concrete proposal, accompanied by estimates of how much it would cost globally to (i) halve the rate of tropical deforestation, (ii) monitor wildlife and embark on programmes to detect and control the spread of potentially deadly viruses and bacteria among domesticated animals, and (iii) stop illegal trade in wildlife. The authors estimate the net prevention costs of these actions to be in the range US$20–30 billion per year, a pittance when compared to the devastation pandemics are known to have brought. The world may lose at least US$5 trillion in GDP in 2020, not accounting for the willingness to pay for lives lost and deaths caused by disrupted medical systems. This makes the estimate of the present value of prevention costs for 10 years around 2% of the costs of the COVID-19 pandemic.

4.8 Core of the Review

Studying our aggregate demand $(Ny/\alpha_X + Ny/\alpha_Z)$ and the biosphere's aggregate supply $G(S)$ allows us to unravel the proximate factors affecting our relationship with Nature. They consist of humanity's numbers (N), our wants and desires (summarised in y), the efficiency (α_X, α_Z) with which we make use of

[152] As elsewhere in the Review, we use expressions that could suggest organisms have intention. But as noted previously, such expressions are used routinely among scientists with no such intention, as for example when they say Nature abhors a vacuum.

[153] The host population may not be human of course. Laboratory experiments in animals, and models of the spread of transmittable diseases among farm animals are routine.

[154] Using a modified version of the model in Anderson and May (1991), Barrett and Hoel (2007) studied the theoretical underpinnings of the optimum management of infectious diseases. Their pioneering paper appeared in what today should be judge as a prescient symposium on the socio-ecology of infectious diseases in the journal *Environment and Development Economics*, 2007, Vol. 12, Issue 5. The ecologist and evolutionary biologist Simon Levin served as Guest Editor.

the biosphere's goods and services to provide us with our wants and desires, and the biosphere's supply of its goods and services ($G(S)$). These are, however, proximate factors. The Review peers into them so as to unravel the forces that shape those factors and the way they influence one another. Depending on the context, that will require us to study the socio-ecological systems that define in turn households, communities, national governments, and even the world as a whole.

In subsequent chapters, we discuss ways to influence the future trajectories of y and N. Our analysis shows that, fortunately, it may be possible to reduce both projected values of N and y without unacceptable human cost. We also study ways in which the G-function can be raised (e.g. by introducing GM crops).

To find a way to convert the Impact Inequality into an Impact Equality, it pays to imagine the reasoning to be iterative:

We could start by (i) further decoding the regeneration function $G(S)$, (ii) identifying states of the biosphere (S) within which the human enterprise ought to confine itself, and (iii) finding ways to influence our wants and desires (as expressed in y), our numbers (N), and the efficiency with which the goods and services produced by the biosphere (G) is converted into the realisation of our wants and desires (α_X, α_Z). The latter could be, for example, by reducing the enormous waste in the global food system by eliminating agricultural subsidies and deploying the released funds to restore and maintain ecosystems. The aim would be to bring our aggregate demand ($Ny/\alpha_X + Ny/\alpha_Z$) in line with aggregate supply ($G(S)$), or in other words, to find ways to satisfy the Impact Equation. We could then search for ways to raise α_X and α_Z while simultaneously study the trade-offs that are involved between the standard of living (y) and numbers (N). Iterating the procedure would require selecting a different value of S and conducting another round. The aim would be to continue the iterative process until we are able to reach what the philosopher John Rawls famously called a *reflective equilibrium* (Rawls, 1972), always bearing in mind that the search involves peering into possible states of affair far from where we may happen to be at (the tipping points). The programme of work involves thought experiments, model building, and empirical investigations.

To contemporary sensibilities, this mode of reasoning could appear strange, perhaps even repulsive. Some would invoke the language of rights. Should S not be determined by market forces? Whose business is it to choose y_i if not household i? Should N not be left to the personal choices of individual couples? And who other than entrepreneurs know how best to devise α_X and α_Z? And should the G-function not be left to be enhanced by agronomists, energy specialists and technologists?

There are several reasons these questions misread the socio-ecological world entirely. The stresses humanity has inflicted on the biosphere to the point where our mode of conduct is not sustainable are due to *institutional failure* writ large. That failure is not only due to malfunctioning markets, but also to households, communities and states. Ultimately, the finger should point to we citizens. Chapters 7 and 8 (environmental externalities) and Chapters 9 and 10 (reproductive externalities) provide an outline of the source of that overarching failure and relates it to fundamental properties of the biosphere we have studied in the previous chapter. When they are taken together, it is apparent that we are far removed from the model of the world that has shaped the contemporary reading not only of economic growth but also of economic development. Economics provides a remarkably effective language in which to read the socio-ecological world. The problem is not with economics, it is rather the fundamentally flawed reading of the structure of economic reasoning. The Review will use examples and illustrations to provide a language for identifying institutional arrangements that align the incentives facing various actors in an economy, so as to protect and sustain our place in the biosphere. It is a fundamental misconception of economists that we can continue to rely on models of growth and development in which our impact on the biosphere is of second-order importance (Chapter 4*). This

Review is an attempt at constructing a formulation of economic reasoning that has the biosphere always in sight. Much remains to be done in advancing the subject; this is only a start.

Annex 4.1 Biodiversity Loss and Climate Change

Climate change and biodiversity loss are intimately related. It is predicted that climate change could overtake land-use change as the leading cause of biodiversity loss by 2070 (Newbold, 2018). Biodiversity loss will in turn have huge implications for climate change: enormous amounts of carbon are locked within animal life and vegetation. The Amazon contains an amount of carbon equivalent to a decade of global human emissions (Lovejoy and Hannah, 2019). Therefore, mitigating against the worst effects of climate change will have significant benefits for biodiversity, and avoiding biodiversity loss will have a positive effect on climate change. As the climate changes, people will need to adapt to new conditions, and employ strategies that deliver for humanity, biodiversity, and the climate simultaneously.

A4.1.1 The Relationship between Biodiversity, Climate Change, and People

Human-induced climate change is leading to changes in precipitation, seasonality, storm intensity, and more.[155] All ecosystems, marine, terrestrial and freshwater, are affected; the ways in which people relate to Nature will be significantly altered. An integrated response to climate change and biodiversity loss is needed, which is made difficult by the fact that different institutions are responsible for each (for example, the UN Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD)). Ecosystems, and the biodiversity they contain, are being altered by climate change, but can also help us adapt to and mitigate its effects (see Chapter 19 for discussion on Nature-based solutions).

Climate change will alter the way we relate to Nature. People living in rural areas will find that the food they can grow – and where they can grow it – changes, people in cities will find that there are higher costs of importing fuel, and supply chains for consumer goods will have vastly different environmental impacts. We need to understand the relationships between people and Nature, and how they are affected by climate change, in order to help the best elements of that relationship to be maintained – or even improved, where new relationships with Nature will be forged because of climate change

How can positive outcomes be achieved for people and ecosystems in different contexts as the climate changes? For example, communities living with coral bleaching face lowered fishery output and reduced income from tourism. Life with climate change looks very different for this community: a planned response may maintain some fishery output through creating climate-adapted habitats for reef fish. Without a response that considers climate change, the community could face loss of all benefits from the reef.

Different aspects of an ecosystem are affected differently by climate change and have roles in its recovery. For example, after reef bleaching, recovery is a race between recolonising corals and the algae that grow on the dead reef. Parrotfish are among the most effective consumers of algae, and they are also negatively affected by climate change. Helping protect parrotfish will help the reef recover, and maintain reef fishery output and communities' livelihoods. So, a short-term reduction in fishing is needed in order to maintain the reef fishery's long-term productivity.

A4.1.2 Climate-Related Changes to Biodiversity are Already Being Observed

Climate change is already harming biodiversity in many ways. Here we discuss a selection: globally coherent patterns of species distribution shifts; impacts on marine ecosystems, particularly coral reefs; and genetic signatures of climate change.

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[155] This section summarises from Lovejoy and Hannah's excellent 2019 work on biodiversity and climate change (Lovejoy and Hannah, 2019).

Species ranges are shifting towards the poles. This has been identified as a climate change 'signal'. Meta-analyses have shown that about half of species on which there were data had changed their distributions significantly over the past 20 to 140 years (Lovejoy and Hannah, 2019). Boreal species diversity in the Yukon, Canada, increased over a 42-year period, during which temperatures increased by 2°C (Research Northwest and Morrison Hershfield, 2017; Lovejoy and Hannah, 2019). The poleward shift trend is consistent across taxa. Marine species are moving towards poles more quickly than those on land. Meta-analyses show that the speed of the leading edge of marine species distribution change is many times greater than the terrestrial, at ~72 km/decade. Poloczanska (2013) compared dynamics in marine species range and found that the leading edges of poleward range shift were expanding nearly five times faster than the trailing edges were contracting, which matches the trend seen in European butterflies. 63% non-migratory European butterfly species expanded their northern range boundary, but only 3% contracted their southern range boundary (Parmesan et al. 1999).

Climate change is already contributing to rapid, broad-scale ecosystem changes, with significant consequences for biodiversity. Several changes have already occurred at spatial scales sufficiently broad to represent biome changes. For example, inland water systems have already been significantly altered, and the spatial scale of changes in fire and precipitation frequency cover large proportions of tropical and boreal biomes respectively (Gonzalez et al. 2010; IPCC, 2014). Rapid broad-scale changes differ from other patterns in vegetation dynamics in that they represent a 'crash' in one or more populations over large areas. Climate triggers these through megafires (as seen in Australia in late 2019 to early 2020), drought-triggered die-off, floods and hurricanes. Pest and pathogen outbreaks are frequently associated with these events, though the relationship between pests and pathogens and climate change is complex (Rosenzweig et al. 2001; Jactel, Koricheva, and Castagneyrol, 2019).

Studies show impacts on individual species and communities, as well as changes at the biome level. Parmesan (2006) reviewed studies that had focused on single species. For example, populations of the well-studied butterfly *Euphydryas editha* are observed to be declining due to warming causing their host plants to senesce before the insects diapause (a period of suspended development in their lifecycle), leading larvae to starve (Hellmann, 2002; Singer and McBride, 2012).

The changing climate is also altering marine biomes, including unique megadiverse systems such as coral reefs. The ocean plays a crucial role in stabilising the Earth System, mainly due to its huge capacity to absorb CO_2 and heat while experiencing minimal change in temperature. The ocean has absorbed 93% of the extra energy existing due to the greenhouse effect, and approximately 30% of human-generated CO_2. These absorptions have had an impact: sea levels have risen, sea ice extent has decreased and ocean pH has dropped rapidly, which is associated with concentrations of key ions such as carbonate and bicarbonate. Oxygen levels are being driven down in deeper areas of the ocean; oxygen-dependent organisms are beginning to disappear from these so-called 'dead zones'. Elsewhere, levels of productivity are rapidly increasing or decreasing due to retreating ice, changing winds, and altering nutrient compositions (Pörtner et al. 2014).

Coral reefs only occupy 0.1% of Earth's surface, but they provide habitat for 25% of known marine organisms (Hoegh-Guldberg, 2019). Coral reefs have experienced small shifts in temperature and ocean chemistry over the past 420,000 years at least. This is due to the fact that even large environmental changes, such as shifts between ice-ages and interglacial periods, are experienced as small changes over relatively long periods of time compared to the current pace of change. The great barrier reef has waxed and waned in the past as sea levels have risen and fallen, but today's pace of change makes current fluctuations more significant. As much as 75% coral reefs are threatened, and as much as 95% is in danger of being lost by 2050 (Hoegh- Guldberg, 1999; Hoegh-Guldberg et al. 2007). Reef-building corals have contracted over the past 30–50 years, which is associated with loss of reef 3D structure (Bruno and Selig, 2007). Reef-building corals rely on the symbiosis between coral and small photosynthetic organisms (*Symbiodinium*). Rapid temperature and pH changes cause this symbiosis to break down, leading to coral bleaching (Glynn, 1993; Hoegh-Guldberg, 1999). Around 1980, large-scale bleaching began in tropical regions, with no precedent in scientific literature; these bleaching events were associated with short periods where maximum sea temperatures rose by 1–2°C (Hoegh-Guldberg, 1999). Reefs occasionally recover from bleaching, but most do not. Protecting the remaining 10% of coral reefs will deliver huge benefits for biodiversity, ecosystem services and human well-being (IPCC, 2014). Climate change mitigation will form an important part of this response, but should take place alongside conservation and restoration efforts (such as the expansion of the marine protected area networks) (IPCC, 2014).

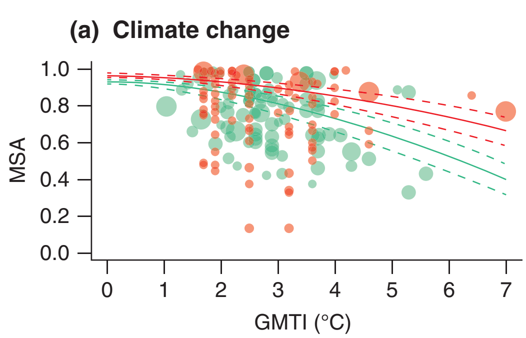
In addition to its impact on coral reefs, ocean acidification has been responsible for changes in animal behaviour: reductions in gastropod shell thickness (due to reduced calcification as a result of reduced pH) lead to enhanced escape activity when a predator is present, demonstrated in a study on *Littorina littorea* (Bibby et al. 2007). Another example is foraging in deep-sea urchins, which increased under lowered pH conditions, possibly to compensate for reduced ability to detect food (Barry et al. 2014).

As well as changing species distribution and altering ecosystems, climate change has already left signatures in organisms' genomes. Selection for genes enabling organisms to survive in warmer temperatures has been identified: an example is changes to the mitochondrial DNA (mtDNA) *NADH* gene in American pika (*Ochotona princeps*, a small relative of rabbits and hares), suggesting local adaptation to different thermal and respiratory conditions (Lemay et al. 2013). Spatially divergent selection of climate-associated genes in oak trees (*Quercus lobata*) has also been observed, including genes involved in bud burst and flowering, growth, and osmotic and temperature stress (Sork et al. 2016). Evolution is a stochastic process, dependent on the genetic options available and their underlying architecture, so we can never be entirely certain about how change will happen. As well as genetic evolution, environmentally determined plasticity is an important aspect of adaptation to changing temperatures: examples include increases in body size in marmots, and changes to clutch size in birds (Hoffmann and Sgró, 2011).

A4.1.3 What Does the Future Hold?

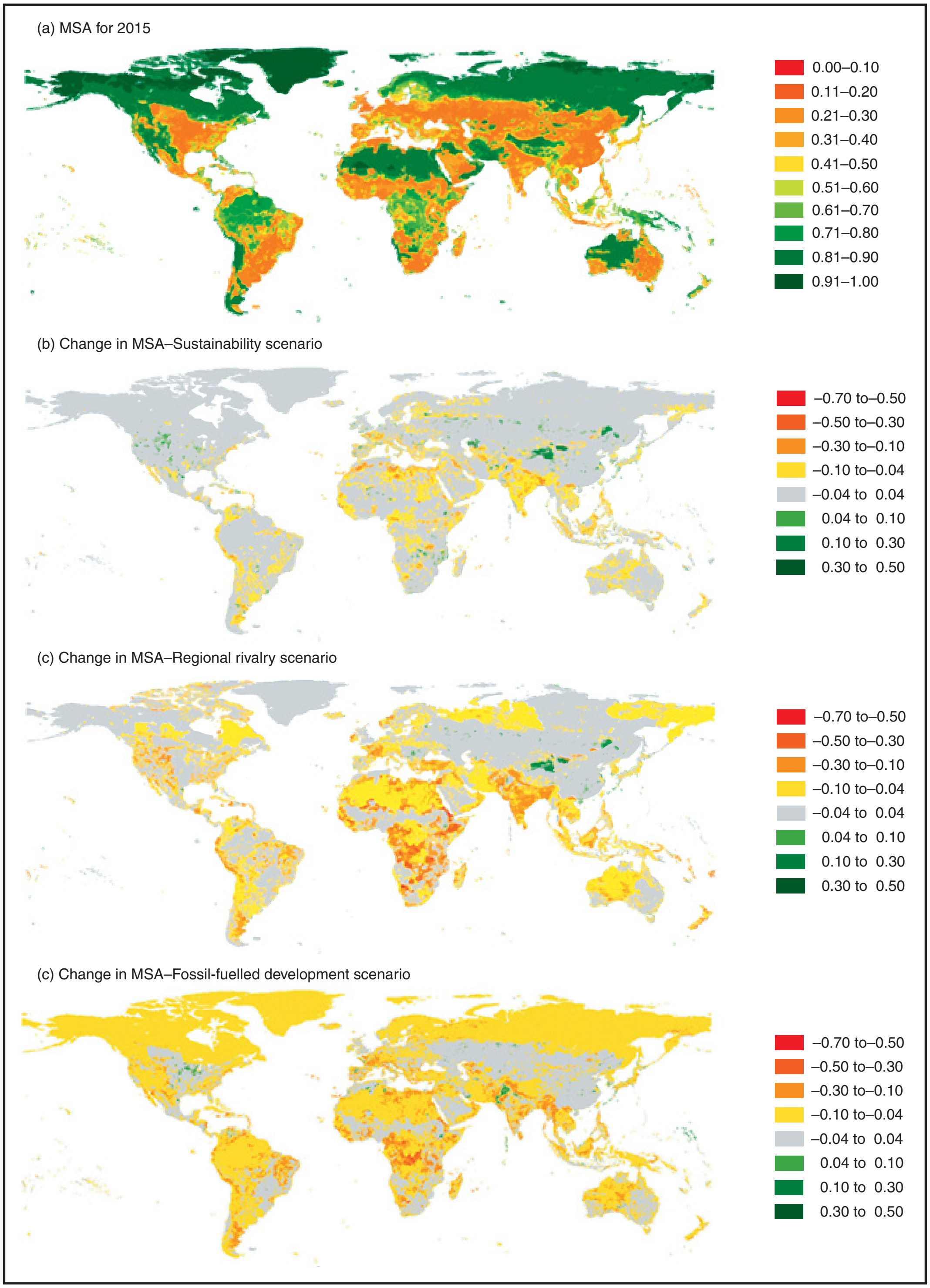
Biodiversity changes have been projected under different scenarios, combining climate change and mean species abundance, showing the negative correlation between temperature rise and species abundance for plants and warm-blooded mammals (Figure A4.1, Schipper et al. 2019).

Figure A4.1 Mean Species Abundance (MSA) Plotted Against Global Mean Temperature Increase (GMTI)



Source: Schipper et al. (2019). Note: Red: warm-blooded mammals; green: plants.

Figure A4.2 Change in Mean Species Abundance (MSA) under Different Scenarios



Source: Schipper et al. (2019). Note: Scenarios represent combinations of shared socio-economic pathways (SSPs) and representative concentration pathways (RCPs).

Schipper et al. (2019) used three shared socio-economic pathways (SSPs) to project changes in mean species abundance (MSA) to 2100, each associated with different pressures placed on the environment by human activity. Even in the most sustainable scenario[156], global changes in MSA are projected to be negative. The regional rivalry scenario projects high population growth and resource-intensive consumption, while the fossil-fuelled development scenario is also characterised by a consumption-oriented society, which is even more energy-intensive. Both lead to high levels of climate change, and widespread negative changes to MSA. Future impacts of climate change on marine biodiversity are discussed in Chapter 16.

Climate change is affecting, and will continue to affect, tropical forests. These forests play a huge part in regulating global climate, accounting for a third of land surface productivity and evapotranspiration (Malhi, 2012). Forest biodiversity will be affected, as tropical forests fall outside their historic climate variability ranges up to a decade faster than any other major terrestrial ecosystem (Mora et al. 2013). Mean land surface temperatures for tropical forest regions are expected to increase by at least 3°C this century (Zelazowski et al. 2011) which is similar to the warming extent of the Paleo-Eocene Thermal Maximum (around 55.5 million years ago), but occurring at an unprecedented speed. This will cause more intense dry seasons, stronger and more frequent droughts, and stronger, longer-lasting heat waves (Malhi et al. 2014). Eastern Amazonia in particular will experience significant declines in total rainfall (IPCC, 2014). There is evidence that tropical trees have narrower thermal niches than temperate trees (Araújo et al. 2013). The effect of increased productivity from increased CO_2 concentration may have a compensatory effect, however, the narrowness of the thermal niche will probably cause a marked decline in fitness for most tropical forest systems.

The decline in fitness and rainfall in the Amazon in particular will have serious consequences for the entire Earth System. At the moment, the Amazon acts as a planetary cooling system, influencing global circulation of air and vapour by evaporating vast amounts of water into the Earth's atmosphere. Even in long dry seasons, the deep-rooted Amazon trees absorb water many metres below the soil surface. Deforestation has reduced the amount of vapour in the atmosphere, leading to reduced rainfall in neighbouring areas, and climate-induced decline in forest fitness would have similar consequences. Where light penetrates to the forest floor, fires become more likely, releasing large amounts of carbon into the atmosphere, and contributing to the greenhouse effect. An estimated amount of carbon equivalent to a decade's worth of human emissions is stored within the wood of Amazon trees. Releasing it through burning would have disastrous consequences for global warming (Lovejoy and Hannah, 2019).

Annex 4.2 How Many People Can Earth Support in Comfort?

The Impact Inequality (Ch. 4) represents the imbalance between our demand for Nature's provisioning goods (i.e., our ecological footprint) and Nature's ability to meet that demand on a sustainable basis.[157] It represents the difference between demand and sustainable supply at a point in time. We expressed the inequality as $Ny/\alpha > G(S)$, where N is global population, y is global per capita final output, or global GDP, α is the efficiency with which Nature's provisioning goods are converted into final output, S is a scalar measure of the stock of biosphere, and $G(S)$ is the biosphere's net regenerative rate. Currently

[156] Figure A4.2 b, which is characterised by relatively low population and consumption growth, less resource-intensive lifestyles such as lower red meat consumption, increased use of resource efficient technologies, more protected areas, and improvements in agricultural efficiency which lead to reforestation.

[157] Because land use changes directed at increasing the supply of provisioning goods diminish Nature's ability to supply maintenance and regulating services, we could equally have interpreted the Impact Inequality as the gap between demand and supply of maintenance and regulating services.

the ratio of global demand to sustainable supply is approximately 1.7, whence the saying that we would need 1.7 Earths if our current demand was to be met on a sustainable basis.

We have presented the Impact Inequality for the global economy. The corresponding inequality for a national economy (or for that matter for a village community) would require a further term representing the impact on the biosphere arising from exchange with others, involving trade and environmental externalities. It is a simple matter to conceptualise that. So, for brevity we continue to adopt a global perspective.

To convert the inequality into an equality requires that either Ny/α be reduced or $G(S)$ be increased, or both. In Part II (Ch. 18–19) we study ways in which investment in Nature can be used to raise $G(S)$. In the chapters that follow in Part I, we uncover institutional changes and practices that would help to reduce Ny/α.

The Impact Inequality tells us that, if we are to hold our ecological footprint fixed, then other things equal, any increase in N would have to be compensated by a reduction in y, or, conversely, any increase in y would require that N be lower. In Ch. 4* we construct a dynamic model of global economic possibilities. Among other things, the model displays the relationships over time between N, y, α, and $G(S)$. It uncovers the choices over consumption and various forms of investment the global citizen (we previously referred to her as the 'social evaluator') faces over time. But because it is prudent to proceed step by step, the model in Ch. 4* does not specify human institutions, nor does it make assumptions regarding human behaviour; instead, it is couched exclusively in terms of *stocks* (of capital assets) and *flows* (of the stocks' yields and our consumption and investment rates). Ch. 13* rectifies this by uncovering the conditions our choices over consumption and various forms of investment must satisfy if they are to lead, in the social evaluator's judgment, to the ethically best future. Economists label such choices as *socially optimal choices*.

In Box 4.6 it was shown that if our collective aim is to close the gap between Ny/α and $G(S)$ by 2030, then on the assumption that the global economy will continue to enjoy the average annual growth rate in GDP of recent decades, we would require the efficiency parameter α to increase at an annual percentage rate some *four* times the rate that has been experienced in recent years. That is so unlikely a scenario that we now study the interplay of N and y in bringing about a sustainable state of affair today. To do that it is simplest to avoid studying social optimum policies, but instead ask a more restricted question: *How many people can Earth support in comfort*? The idea is to hold all else constant and determine the value of N at which the human ecological footprint equals the biosphere's net regenerative rate at a comfortable standard of living y.[158]

There is a commonplace intuition that the current imbalance in our demand for Nature's provisioning goods is due to high consumption among the world's rich people; with an accompanying corollary that large additions to human numbers over the past 70 years – N having risen from approximately 2.5 billion to 8 billion – has had little to do with it. The intuition is at variance with evidence. Suppose, for example, the 1.5 billion inhabitants of OECD countries (the *Economist* newspaper calls the OECD "a club of mostly rich countries") were to accept a *halving* of their annual incomes from the current figure of 40,000 international dollars per person to 20,000 international dollars. That's a huge drop in incomes, but as the Impact Inequality shows, the move would reduce the imbalance from the current ratio of 1.6 to 1.2. And 1.2 is a substantial figure, implying further erosion of the biosphere at a fast pace.

So, we now choose a value of y at which life is deemed to be comfortable. Per capita global GDP in 2019 was approximately 16,000 dollars at 2011 prices. As an exercise let us take the chosen y to be 20,000 international dollars at 2011 prices. As the figure falls in the range of per capita

[158] The analysis that follows is taken from Dasgupta, Dasgupta, and Barrett (2023).

incomes in the World Bank's list of high middle-income countries, we use it to represent a comfortable standard of living.

We assume that people apply their labour on produced capital and natural capital to produce an all-purpose commodity that can be consumed. As of now we have little quantitative knowledge of the biosphere's dynamics when viewed in the aggregate (i.e., we have no estimates of the *G*-function in the Impact Inequality). But as produced capital is complementary to natural capital in production (any expansion of the former makes further demands on natural capital), an expansion of the stock of the former depresses the stock of the latter, other things equal. We noted previously (Sec. 4.1.2) that Rockström et al. (2009) have found evidence in the Earth system's signatures that several planetary boundaries are so close to being breached, that further deteriorations in the state of the biosphere would take it into terrains that are unchartered and therefore should be avoided. Let us then regard K to be an aggregate measure of produced capital and natural capital and hold it fixed to ensure that there is no further deterioration of the biosphere. The idea is to stop K on its tracks by a global quota on what we are permitted to take from the biosphere.[159]

Let Q be aggregate output. In Ch. 4* we construct a complete model of economic possibilities involving produced, human, and natural capital. Here we present a truncated version of it. If global population is N and φ the proportion of N in production, we assume that output Q is a power function of K and N, that is,

$$Q = K^{(1-\rho)}[\varphi N]^{\rho}, \qquad 0 \leq \rho < 1, 0 < \varphi < 1 \tag{A4.2.1}$$

We now estimate $K^{(1-\rho)}$ from the current size of the world economy.

For want of data to the contrary, we assume that the value of the world's production of final good and services draws proportionately on all ecosystem services. In 2019 world output was about 120 trillion dollars at 2011 prices. Using the model of production in equation (A4.2.1), we therefore have

$$K^{1-\rho}[\varphi N]^{\rho} = 120 \text{ trillion dollars} \tag{A4.2.2}$$

World population was 7.8 billion in late 2019. The global dependency ratio, that is, the ratio of the sum of the number of people below age 15 and above age 65 to the number of people between 15 and 65, is today about 1.6 to 1. Thus $\varphi = 1/2.6$, which means $\varphi N = 3$ billion. A huge empirical literature in economics suggests that as a rounded figure, $\rho = 0.5$ is not unreasonable. Equation (A4.2.3) then says,

$$\begin{aligned} K^{0.5} &= 120 \times 10^{12}/\left(3 \times 10^{9}\right)^{0.5} \text{ dollars per producer}^{0.5} \\ &\approx 2.2 \text{ billion dollars per producer}^{0.5} \end{aligned} \tag{A4.2.3}$$

Having calibrated our model of global production, we compute the sustainable population size if $y =$ 20,000 dollars. Let N^* denote the size of the sustainable global population. To err on the conservative side of the size of the Impact Inequality today, we assume that the global ecological footprint is currently 1.5. That means if the biosphere and the stock of produced capital were stopped on their tracks, their sustainable value would be $K/1.5$, which we denote by K^*. Using equation (A4.2.3),

$$(K^*)^{0.5} \approx 1.8 \text{ billion dollars per producer}^{0.5} \tag{A4.2.4}$$

Using eq. (A4.2.2) – (A4.2.4), we have

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[159] Quotas are applied routinely to fisheries and forestry, and for access to potable water in dry regions. The recent international agreement to limit the rise in mean global temperature to 1.5°C above what it was in pre-industrial times is tantamount to the use of quotas in emissions. Wilson (2016) has made an impassioned plea to leave half of Earth free of human encroachment. We follow that route to identify a sustainable socio-ecological state.

$$(K^*)^{0.5}(\varphi N^*)^{0.5} = [1.8 \times 10^9](\varphi N^*)^{0.5} = \left(20 \times 10^3\right)N^* \tag{A4.2.5}$$

But $\varphi = 1/2.6$. From eq. (A4.2.5)) it follows that,

$$N^* \approx 3.3 \text{ billion} \tag{A4.2.6}$$

Global population was about 3 billion in 1960 (Fig. 4.2); which means, in 3.3 billion we have arrived at a figure that prevailed only about 60 years ago. As the finding in Fig. 4.10 showed, if inequality in the distribution of incomes was judged to be inevitable, the size of global population that would support an average income of 20,000 international dollars would be smaller.

But even a global population of 3.3 billion seems so foreign to us today that the above exercise should probably be interpreted less as prescription than as a sign of how quickly we have overstrained Nature. The idea of sustainable development is meaningless unless it ensures that it does not carry with it the Impact Inequality. Subject to all the caveats we have stressed, our finding says that if humanity were to find ways to reside in the biosphere in a sustainable manner and to bring about economic equality, the human population Earth could support at a living standard of 20,000 dollars is approximately 3.3 billion. It is a simple matter to conduct the exercise with alternative figures for the living standard. We resist doing that.

It is informative to flip the question underlying the calculation by asking what living standard we could aspire to if world population was to attain the UNPD's near lower-end projection for 2100 of 9 billion (UNPD, 2019b). Equations (A4.2.4) – (A4.2.5) provide us with the tools needed to provide an answer. Sustainability requires that,

$$\left(1.8 \times 10^9\right)(\varphi N)^{0.5} = Ny \tag{A4.2.7}$$

Set $\varphi = 1/2.6$ and $N = 9$ billion. That means equation (A4.2.7) reduces to

$$[\left(1.8 \times 10^9\right)\left(9 \times 10^9/2.6\right)^{0.5}]/9 \times 10^9 = y \tag{A4.2.8}$$

Let y^* denote the solution of equation (A4.2.8). Then we have $y^* \approx 11{,}840$ dollars at 2011 prices. The figure falls within the range of middle-income countries. But 11,800 dollars at 2011 prices was the global living standard in about year 2000 (Fig. 4.3). At that time, however, world population was only a little over 6 billion. That 3 billion fewer people did not enjoy a higher living standard should not surprise, because the global stocks of produced capital and human capital were a lot less 20 years ago than it was in 2019 and our model was calibrated with the stocks in year 2019.

How should we read these exercises? It would be easy enough to dismiss them for their naivety, for example that they don't allow for the technological advances we should expect to be made to enable even 9 billion people to enjoy a standard of living a lot higher than 11,800 dollars. But that would be to overlook that unless the global economy finds ways to charge for our use of Nature's provisioning goods, technical advances will continue to be directed at economising on human capital and produced capital and will continue to be rapacious in the use of natural capital. If by some miracle it was possible to make us pay for Nature's services at something like their accounting prices (or social worth), our consumption patterns would be very different. Not only would our household budgets look different, but entrepreneurs would have the incentive to invest in the technologies that economise on the use of natural capital, not be rapacious in its use. The human economy would move in such a different direction that it could even be that our descendants would have a better life than the average person does currently. Today, much of Nature is free, and we add to that insult by subsidising its exploitation to the tune of some 4–6 trillion dollars annually. That makes Nature come to us with a *negative* price! Our efforts should be directed at so improving our institutions that these distortions are eliminated.