# The Dasgupta Review – Independent Review on the Economics of Biodiversity

## Interim Report

April 2020

# The Dasgupta Review – Independent Review on the Economics of Biodiversity

## Interim Report

April 2020

This publication is available at: www.gov.uk/official-documents.

Any enquiries regarding this publication should be sent to us at
public.enquiries@hmtreasury.gov.uk

ISBN 978-1-913635-26-8 PU2964

# Contents

# Introduction

Our economies, livelihoods and well-being all rely on Nature. We rely on Nature to provide us with food, water and shelter; to regulate our climate and control disease; to maintain nutrient cycles and oxygen production; and to provide us with spiritual fulfilment and opportunities for recreation, among many other examples. Put simply: without Nature, there would be no life.

Biodiversity plays an important role in the provision of many of the services we receive from Nature, known today as *ecosystem services* or *nature's contributions to people*. Just as diversity within a portfolio of financial assets reduces risk and uncertainty, diversity within a portfolio of natural assets – *biodiversity* – directly and indirectly increases Nature's resilience to shocks, reducing risks to the services on which we rely. Biodiversity is an essential characteristic of Nature. The economics of biodiversity is therefore the economics of Nature.

But Nature's resilience is being severely eroded, with biodiversity declining faster than at any time in human history. In the past four decades, there has on average been a 60% decline in the populations of mammals, birds, fish, reptiles, and amphibians, mostly in the tropics. The estimated number of wild bee species worldwide has fallen from 6,700 in the 1950s to only 3,400 in the 2010s. It is thought that one million animal and plant species (approximately 25%) are threatened with extinction in most of the animal and plant groups that have been studied. Current extinction rates are around 100 to 1,000 times higher than average over the past several million years – and they are accelerating.

The majority of ecosystem services are also in decline, including those that regulate and maintain our life support systems. Many of these ecosystem services and the ecosystems that provide them are irreplaceable. Critical ecosystems like the Amazon, which has already lost 20% of its original extent, are reaching tipping points. In the case of the Amazon, there is a risk it will shift from rainforests into savannah. Changes in land and sea-use, over harvesting, climate change, invasive alien species, and pollution of air, water, and the soils, are significant drivers of biodiversity loss.

Biodiversity loss is also intimately related to climate change. Indeed, climate change may become the major driver of biodiversity loss in the coming decades. Land use change which entails biodiversity loss – in particular deforestation – is, and could continue to be, a significant contributor to climate change. Protecting and enhancing biodiversity will help us address climate change, by helping both to mitigate climate change by storing and sequestering carbon in ecosystems, and to adapt to the inevitable effects of unavoidable climate change. For example, coastal ecosystems mitigate the increasing risks from natural hazards like floods and storms.

It comes as no surprise, therefore, that successive international reports have warned that the current high rates of biodiversity loss pose a major risk to our economies and our way of life, and that urgent action is needed, including the recent Global Assessment of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), and the World Economic Forum's most recent Global Risks Report (World Economic Forum, 2020), which ranked biodiversity loss and ecosystem collapse in the top five risks. For the first time, all the top five global risks, in terms of likelihood and severity of impact, were environmental.[1]

Following millennia in which Nature was broadly resilient, a variety of compelling scientific evidence shows that humanity's demands on Nature are outstripping its ability to meet that demand on a sustainable basis. The difference is a measure of the rate at which Nature is being run down. Simple estimates of our total impact on Nature suggest that maintaining the world's current living standards with our current economic systems, fuelled by unsustainable production and consumption, would require 1.7 Earths.

Earth scientists have named the new age we have entered 'the Anthropocene', in which human activity has become the dominant influence on the biosphere. Economic growth has put such strain on the biosphere that economists are now being urged by environmental scientists to re-judge our relationship with Nature if we are to protect and enhance both biodiversity and our prosperity.

*The Dasgupta Review* ('the Review') will explore the sustainability of our engagements with Nature – what we take from it; how we transform what we take from it and return to it; why we have disrupted Nature's processes; and what we must urgently do differently to enhance our collective wealth and well-being, and that of our descendants.

The COVID-19 pandemic has already devastated lives and livelihoods around the world and will have deep and lasting economic consequences. At a time when we are all confronting a global pandemic, a review on the economics of biodiversity is even more relevant.

First, the health of our planet plays an important role in the emergence and spread of infectious diseases. Land-use change has been identified as the leading driver of recently-emerging infectious diseases (Patz et al., 2000; Jones et al., 2008; Loh et al., 2015). Deforestation, conversion of primary forest for intensive agriculture and extractive industries such as logging, mining and plantations, and illegal wildlife trade are causing both biodiversity loss and contributing to the emergence and spread of infectious diseases. One important factor is increasing contact among people and wildlife that carry zoonotic pathogens as human activity expands. This leads to 'spill-over infections' where pathogens are transmitted from animals to human hosts. The havoc that COVID-19 is causing underscores the importance of biodiversity for our health and that of the global economy, and ultimately the need for the human enterprise to live within the 'safe operating space' of the biosphere.

---

[1] In addition to biodiversity loss and ecosystem collapse, the top five risks included extreme weather events with major damage to property, infrastructure and loss of human life; failure of climate-change mitigation and adaptation by government and business; major natural disasters; and human-made environmental damage and disasters, such as oil spills.

Second, as we emerge from the current health crisis, there will be an opportunity to reflect on what we mean by, and how we achieve, economic prosperity. In setting out a unified framework for thinking about the economics in a way that fully accounts for Nature and the risks that emerge from loss of Nature, the Review should be seen as a contribution to that reflection.

# Executive summary

In March 2019, HM Treasury, the UK government's economic and finance ministry, commissioned an independent, global review on the economics of biodiversity.

The Review is led by Professor Sir Partha Dasgupta – Frank Ramsey Professor Emeritus of Economics at the University of Cambridge – and assisted by an interdisciplinary team based at HM Treasury. The Review is supported by an Advisory Panel drawn from public policy, science, economics, finance and business.

The Review was asked by the UK government to assess the economic benefits of biodiversity, and the economic costs of biodiversity loss; and identify actions which can protect and enhance both biodiversity and economic prosperity. The primary audience for the Review is economic and finance decision makers in the public and private sector. The Review aims to shape the international response to biodiversity loss, including the successors to the Aichi Biodiversity Targets, and inform global action to deliver the UN Sustainable Development Goals (UN SDGs).

The final Review will be published in advance of the fifteenth meeting of the Conference of the Parties (COP15) to the Convention on Biological Diversity (CBD), which is due to be held in Kunming, China.

This interim report sets out the economic and scientific concepts, which will underpin the final Review. The interim report stops short of presenting options for change – these will be set out in the final Review.

**Chapter 1** explains the Review's scope. This includes setting out how and why the Review approaches the economics of biodiversity as the economics of Nature; acknowledging that humanity and our economies are *embedded* in the biosphere; and explaining the Review's use of proxies for biodiversity. Chapter 1 also explains the Review's draft two-part structure: 'Part I – Foundations' will set out a formal framework for the economics of biodiversity; 'Part II – Options for change' will apply the intellectual foundations of Part I to present options for change.

**Chapter 2** provides a preview of the key economic and scientific concepts which will underpin the final Review. These include the need to:

- recognise that biodiversity is an essential characteristic of Nature, playing an important role in the provision of 'ecosystem services' on which our economies and livelihoods rely;
- view Nature as an asset, just as produced and human capital are assets, and acknowledge that we are failing to manage our assets efficiently;
- understand the loss of Nature as an asset management problem, and that we must manage our overall stock of all capital assets more efficiently;

- understand how our total demand on the goods and services that Nature provides outstrips its ability to supply those goods and services on a sustainable basis, by way of what the Review calls the *Impact Inequality*;
- accept that addressing the supply-demand imbalance means confronting difficult questions, including questions about what and how we consume, how we manage our waste, and the role family planning and reproductive health can play;
- acknowledge that the human economy is embedded within – not external to – Nature, which helps us to recognise the limits Nature places on the economy and, in so doing, reshape our understanding of sustainable economic growth; and
- revisit our measures of success, including looking beyond GDP in order to maximise our wealth and wellbeing, and that of future generations.

The final Review will apply the framework that is developed to present options for change, including shining a light on many of the success stories around the world that demonstrate what is possible.

Chapter 3 sets out next steps for the Review over the coming months. To support the ongoing work of the Review, feedback is invited and encouraged in response to the detail set out in this interim report.

# Chapter 1
# Scope

1.1 Professor Dasgupta was commissioned to examine the evidence on:

- how biodiversity supports sustainable economic growth;
- the implications of further biodiversity loss for the prospects for economic growth over the coming decades, taking into account the interaction with other aspects of environmental degradation, including climate change; and
- the impact, effectiveness and efficiency of existing national and international actions and arrangements to limit and reverse the loss of biodiversity and their impact on economic growth.

1.2 Based on this evidence, the Review was asked to provide an assessment of:

- a range of scenarios for enhancing global biodiversity compared with business as usual, focusing on the medium to long-term perspective and the relationship with economic growth; and
- the range of best practices, initiatives and interventions for industry, communities, individuals and governments that can simultaneously achieve the goals of enhancing biodiversity and delivering sustainable economic growth, drawing implications for the timescales for action and the range of scenarios above, and recognising the interactions with climate change mitigation and adaptation needs and opportunities.

1.3 In response to its Terms of Reference, the Review will consider the sustainability of how we engage with Nature. It will examine how we are embedded in Nature: what we take from it; how we transform what we take from, and return to, it; how Nature supports our economies and wellbeing; and why we are disrupting Nature so dramatically at great cost to our collective wellbeing.

1.4 The Review will set out a unified framework for thinking about the economics of biodiversity in the context of global goals for sustainable development. In doing so, the Review will reconstruct our economic 'grammar', and rebuild our understanding of economics as a discipline and way of thinking.

1.5 The main concepts of the unified framework are set out in this interim report and will be expanded upon in the final Review, which will also set out options for change to make humanity's engagement with Nature sustainable.

1.6 The Review is global in scope, acknowledging that biodiversity loss affects individuals, households, communities, firms, and governments in different ways, and is influenced by a range of factors, not least location. The Review will attempt to speak to this wide spectrum of experience, based on the most credible, relevant and legitimate evidence and case studies from around the world.

1.7 The Review also builds on the important literature estimating the value of stocks of natural capital and flows of ecosystem services.[1] The Review recognises the importance of these innovations for informing decisions but will not itself produce a valuation of biodiversity or global cost-benefit analyses of biodiversity policies.

## The economics of biodiversity is the economics of the biosphere

1.8 Biodiversity is the variety of life, in all its forms. It has many dimensions, including the diversity and abundance of living organisms, the genes they contain, and the ecosystems in which they live.[2] The chemical reactions of Earth's plants, animals, and microbes sustain life by converting sunlight and nutrients to food, energy and the building blocks of life, as well as recycling waste. The activities of these organisms are often hidden from view, but they enable ecosystems to function and provide many services on which we rely. They maintain a genetic library, preserve and regenerate soil, fix nitrogen, recycle nutrients, control floods, mitigate droughts, filter pollutants, assimilate waste, pollinate crops, operate the hydrological cycle and sequester carbon.

1.9 The *biosphere* is the part of Earth that is occupied by living organisms. It is a self-organising regenerative asset. Ecologists commonly represent the state of the biosphere as a spatial distribution of *biomass*, expressed in, for example, kilograms (kg). Biomass in any location is the total mass of living material in it. The biosphere's regenerative rate is called *net primary productivity* (NPP). It is a spatial distribution of organic compounds that are fixed by organisms (known as primary producers) who obtain energy directly from the sun to produce their own food, minus their respiration per unit of time. During respiration, organic compounds are broken down to fuel the processes that govern a primary producer's activities.

1.10 A useful way to partition the biosphere is in terms of interconnected constituents, known as *ecosystems.*[3] Ecosystems combine the abiotic environment with biological communities (of plants, animals, fungi, microorganisms) that form self-organising, regenerative functional units. *Functional units* refer to combinations of life forms that control fluxes in an environment such as that of energy (e.g. photosynthesis), nutrients (e.g. nitrogen fixation), and organic matter (e.g. decomposition of organic waste). Ecosystems vary enormously depending on a range of factors, such as the underlying geology, climate, nutrient and chemical status of the soils, hydrology, prevailing winds, season, and so on. Some ecosystems are highly diverse, such as the tropical rainforest, while others have low diversity,

---

[1] This includes work on the UN System of Environmental-Economic Accounting, The Economics of Ecosystems and Biodiversity (TEEB), the work of the UK's Natural Capital Committee, the Millennium Ecosystem Assessment, the Natural Capital Protocol, the Natural Capital Project, and UNEP's publications on 'inclusive wealth', among others (Millennium Ecosystem Assessment, 2005; Kumar, 2010; Kareiva et al., 2011; UNU/IHDP-UNEP, 2012,2014; Sukhdev; Wittmer; and Miller, 2014; Natural Capital Coalition, 2016; Managi and Kumar, 2018; Natural Capital Committee, 2020).

[2] The CBD defines biodiversity as 'the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems'.

[3] The biosphere can also be categorised into different *biomes*, which are combinations of ecosystems that have evolved in response to a similar physical climate, such as tundra, grasslands or tropical rainforests.

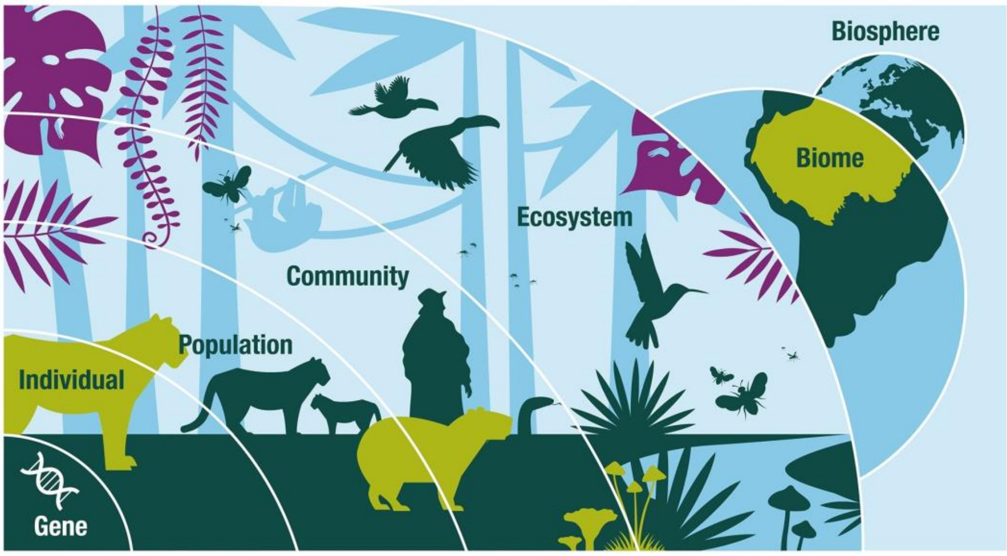
such as polar ecosystems. Some species are extremely rare, existing in only one ecosystem, while others are much more widespread.

1.11 Classification of ecosystems involves informed judgment – ecosystems are not defined in a sharp manner from rigid principles. Watersheds, wetlands, coral reefs, and mangrove forests are ecosystems, as are freshwater lakes, coastal fisheries, and estuaries. As a rule, ecosystems are not discrete entities: they blend into one another. That is why, for clarity, it helps to consider those ecosystems that are tightly knit, with strong interactions among their own constituents and weak interactions across their boundaries. The boundaries may harbour discontinuities, such as in the distribution of organisms, soil types, the depth of a body of water, and so on. Even those ecosystems are interconnected. For example, agricultural farms, which can be extensive tracts of mono-crop fields, are known to leak phosphorus into freshwater lakes.

1.12 Ecosystems differ in their spatial reach (a hedgehog's gut is an ecosystem, as is a tropical rainforest) and rhythmic time (minutes for bacterial colonies, decades for boreal forests). Some ecosystems are of near-continental size (the Amazon rainforest), some cover regions (the Ganga-Brahmaputra river basin), many are volcanic islands (the islands comprising Micronesia), others involve clusters of towns (micro-watersheds in the Ethiopian highlands), while yet others are confined to a village (village ponds in Norfolk, UK).

1.13 Different ecosystems – grasslands or woodlands, freshwater or oceans – are associated with different levels of biomass and NPP. Generally, biodiversity is greater in wetter and warmer places than in drier and colder places. Ecosystems that are biodiverse often have higher productivity than those that are degraded with low biodiversity. However, ecosystems with high biomass do not necessarily have high biodiversity. Farmed systems, for example, have been designed to optimise yield which can lead to high biomass in terms of crops but may not have diversity of species, or other biodiversity attributes. So, measures of biomass and NPP must be put into context to be able to infer other attributes of biodiversity.

Figure 1.A: Components of biodiversity and relationships among biodiversity, ecosystems, biomes and the biosphere




*Note: Graphic of the components of biodiversity.*

1.14 Biodiversity enables Nature to flourish. The variability of species in an ecosystem and the genetic variation within those species enable that ecosystem to respond to change. Organisms have different roles in an ecosystem. This 'functional diversity' influences how ecosystems function and their ability to provide the goods and services on which we depend. Diverse communities are more productive, resilient and able to adapt (Hooper et al., 2005; Cardinale et al., 2012; Tilman, Isbell and Cowles, 2014).

1.15 Ecosystems regenerate. New forests emerge from the ashes of fires, rising from self-sown seeds and shoots from the roots of plants. Biodiversity enables that regeneration to occur. It affects both living and physical parts of ecosystems, which are connected through nutrient cycles and energy flows. Plants release oxygen into the atmosphere; the transpiration of large forests affects weather patterns and the availability of water; and sedimentary rocks and fossil fuels come originally from living organisms.

1.16 The ability to regenerate is affected when ecosystems are under unusual pressure from external drivers, such as human activity. Biodiversity loss compromises the delivery of ecosystem services (Balvanera et al., 2006; Harrison et al., 2014) like pollination[4], and can lead to ecosystem collapse. In marine systems, for example, the dramatic loss of oxygen in parts of our oceans has led to 700 sites worldwide now classified as *dead zones*, with losses in biodiversity and fisheries, increases in greenhouse gas release, and negative impacts on food security and livelihoods (Breitburg et al., 2018; Laffoley and Baxter, 2019).

1.17 Climate change, to take another example, may become the dominant driver of biodiversity loss in the coming decades (Newbold, 2018; IPBES, 2019). Climate change is already contributing to rapid, broad scale ecosystem changes, with significant consequences for biodiversity. 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, 2015). Moreover, land use change – in particular deforestation – is, and could continue to be, a significant contributor to climate change for, among other things, enormous quantities of carbon are locked within the living system (Houghton, Byers and Nassikas, 2015; IPCC, 2015). The Amazon rainforest, for example, contains an amount of carbon equivalent to a decade of global human emissions (Lovejoy and Hannah, 2019). Actions to mitigate and adapt to climate change can deliver benefits for biodiversity. For example, restoring coastal ecosystems like mangrove forests helps to mitigate the increasing risks from natural hazards like floods and storms that climate change brings in its wake. Conversely, biodiversity conservation can help to address climate change through storage and sequestration of carbon in plants, soils, geological formations and the ocean.

1.18 Given these complex interactions among systems, **the economics of biodiversity is the economics of the biosphere** or, more generally, the economics of Nature. This is the scope of the Dasgupta Review.

4 More than 75% of globally important food crops rely on animal pollination, including fruits, vegetables, coffee, cocoa and almonds (Potts et al, 2016).

## Humanity and our economies are embedded within the biosphere

1.19 Humanity and our economies are embedded in the biosphere. The biosphere's future evolution will be strongly influenced by our choices. Conversely, future opportunities for human prosperity depend on the future of the biosphere. This mutual feedback informs the Review.

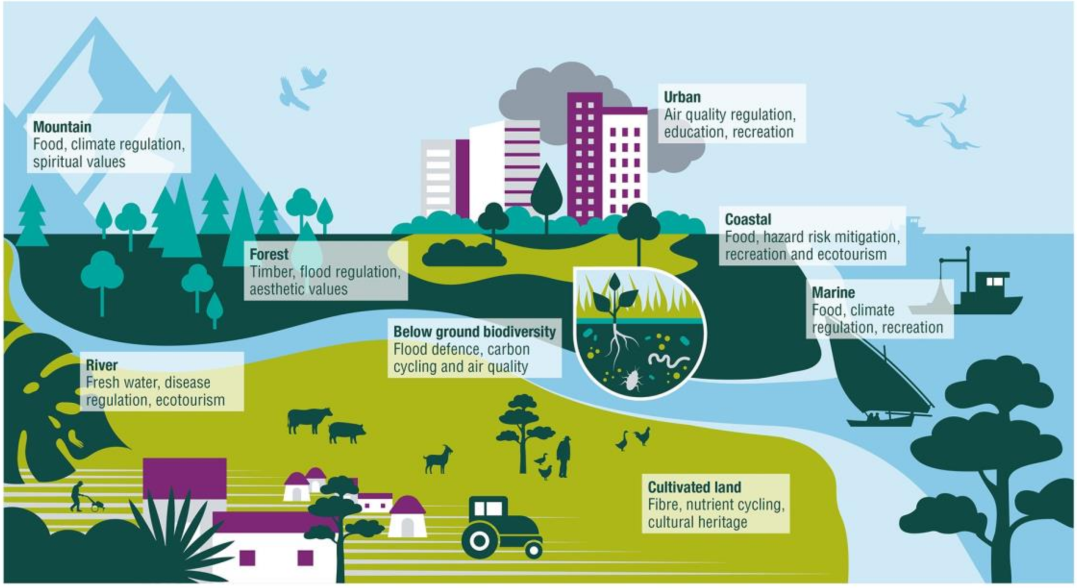
### Figure 1.B: The relationship between the economy and the biosphere

*Note: Graphic of the economy within the biosphere.*

1.20 Box 1.A offers a classification of the myriad of ecosystem services on which we depend for our existence. They include services from the resources we extract and harvest. We also discharge waste, including pollutants, which damage our assets. Acid rain (rainfall made acidic by atmospheric pollution) damages forests; carbon emissions into the atmosphere trap heat; plastic in the oceans harms marine animals; and industrial chemicals reduce water quality in rivers. Natural ecosystems are 'goods', while pollutants, which degrade natural resources, are 'bads'. Pollutants are the reverse of natural ecosystems and polluting is the reverse of conserving (Dasgupta, 1982). The Review uses this equivalence to construct a unified framework for the economics of the biosphere.

1.21 Acknowledging that humanity and our economies are embedded in the biosphere has profound implications. By constructing an account of the global economy as embedded in the biosphere, the Review moves in a different direction from the one that is pursued in contemporary accounts of economic development and growth (Aghion and Howitt, 1998; Barro and Sala-i-Martin, 2003; Helpman, 2004; Acemoglu, 2008; Galor, 2011).

### Figure 1.C: The biosphere's goods and services by biome




*Note: Graphic of the biosphere's goods and services.*

### Box 1.A: Ecosystem services

The Common International Classification of Ecosystem Services (CICES) identifies the contributions ecosystems make to human well-being. The CICES builds on the pioneering work of the Millennium Ecosystem Assessment. It consists of three categories of ecosystem services, contributing directly or indirectly to human well-being. It offers a powerful framework for understanding the central dilemma in the economics of biodiversity: reconciling the competing demands for provisioning services, with the need for regulating and maintenance services and cultural services.[5]

*Provisioning Services* This category comprises the vast range of products we obtain from ecosystems. This includes food, freshwater, fuel (dung, wood, twigs and leaves), fibre (grasses, timber, cotton, wool, silk), biochemical and pharmaceuticals (medicines, food additives), genetic resources (genes and genetic information used for plant breeding and biotechnology), and ornamental resources (skins, shells, flowers).

*Regulating and Maintenance Services* This category regulates and maintains ecosystem processes, including maintaining the gaseous composition of the atmosphere, regulating both local and global climate (temperature, precipitation, winds and currents), controlling erosion (soil retention and prevention of landslides), regulating the flow of water (the timing and magnitude of runoff, flooding, and aquifer recharge), purifying water and

---

[5] The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) reframed ecosystem services with a broader notion of 'nature's contributions to people', which deepens the recognition that culture is central to all links between people and nature. It also strongly recognises other knowledge systems, including those of local communities and indigenous peoples (Díaz et al., 2018).

decomposing waste, regulating diseases (controlling the abundance of pathogens such as cholera, and disease vectors such as mosquitoes), controlling crop/livestock pests and diseases, pollinating plants, and offering protection against storms (forests and woodlands on land, mangroves and coral reefs on coasts), recycling nutrients, and maintaining primary production and oxygen production through photosynthesis.

*Cultural Services* This category comprises non-material benefits that people obtain from ecosystems through recreation, tourism, intellectual development, spiritual enrichment, reflection and creative and aesthetic experiences. They offer life-enriching and life-affirming contributions to human well-being and health. The diversity of life has in part shaped the diversity of cultures: the local ecosystem offers people a sense of place, their cultural landscape; religions attach significance to particular flora and fauna; and people find beauty in Nature, which gives expression in the private demand for gardens and public demands for parks and protected areas.

The flows of these services rely on stocks of natural capital. Over-extraction of provisioning services depletes natural capital stocks, in quality or quantity or both, and has an adverse influence on the abiotic environment. The feedback, taken together, has an adverse effect on the ability of ecosystems to provide regulating and maintenance, and cultural services.

## Using global proxies of biodiversity

1.22 Measuring changes in biodiversity is more complex than measuring climate change. Climate change can be measured in terms of greenhouse gas emissions and carbon dioxide concentrations in the Earth's atmosphere. Given its many dimensions, a variety of measures of biodiversity are needed. The metrics that have been constructed attempt to represent the structure and function of ecosystems, the composition of biological communities, the diversity and traits of species, and genetic composition.

1.23 In parts, the Review examines the issue of biodiversity loss globally using the simple proxy measures of biomass and net primary productivity to represent the biosphere. The size and distribution of biomass and NPP are no doubt crude measures of the state of the biosphere, but they are no more crude than using the size and distribution of produced and human capital and incomes to measure the state of the global economy. The Review recognises that other biodiversity metrics are required to inform policy and practice at sub-global scales, including at scales as local as village economies in developing countries. The Review explores the use of these metrics in case examples of restoration, conservation and sustainable use. The use of the simple proxy measures of biomass and NPP provides a useful framework for the Review but does not diminish the astonishing complexity of the biosphere, nor make it any less important to understand and represent that complexity when making decisions and forming policy.

## Review structure

1.24 The Review's draft structure is split into two parts.

1.25 'Part I – Foundations' will set out a systematic and formal framework for the economics of biodiversity, which will provide the intellectual foundations that underpin the Review. Key concepts addressed in Part I are previewed in Chapter 2 of this interim report, and include:

- viewing Nature as an asset, just as we view produced and human capital;
- understanding and addressing biodiversity loss by viewing it as a portfolio asset management problem;
- understanding and explaining the imbalance between humanity's demands on Nature, and the biosphere's ability to meet those demands on a sustainable basis; and
- a model of economic prosperity that properly accounts for humanity's interaction with, and dependence on, Nature.

1.26 'Part II – Options for change' will apply the intellectual foundations of Part I to present options for change that can both enhance biodiversity and deliver economic prosperity. These options for change will cover a range of levers – including policy, institutions, economic evaluation, finance and technology – and will reflect on the role of the public and private sector, as well as the role of the citizen. The Review will also speak of some of the many success stories around the world to demonstrate what is possible.

# Chapter 2

# Preview: Part 1 - Foundations

## Loss of Nature as an asset management problem

2.1 Ecosystems are assets. This is why Nature is referred to by economists as *natural capital*, akin to produced capital (networks of roads, rows of buildings and so on) and human capital (combinations of health, knowledge, and skills). Consequently, the Review frames the economics of biodiversity as the study of asset management problems.

2.2 In economic terminology, assets are durable objects. Their durability enables us to save them for our own future, offer them as gifts to others, exchange them for other goods and services, and bequeath them to our children. Durable does not mean eternal; durable goods depreciate over time. But unlike services, assets do not disappear instantly.

2.3 The value of an asset is determined by the goods and services it provides over its life. For example, the value of a refrigerator comes from the benefits it provides in preserving food over its lifetime. The lifetime of ecosystems such as tropical forests can be indefinite, given they regenerate. The value of a forest comes from the flow of benefits it will provide: opportunities for recreation and spiritual connection, timber, a clean, reliable supply of water, mitigation of flood risk and so on. The social value of any asset is called its *accounting price*, also known as its *shadow price*.[1] The social value of an asset is important because it represents its value to society as a whole. An asset's accounting price is not necessarily the same as the price at which it is exchanged in the market (or *market price*). Indeed, for many ecosystem services there are no markets at all – they are free goods.

2.4 Depreciation is the decline in the quantity or quality of an asset over time. In the case of natural capital, depreciation is the difference between the rate at which it is harvested and its regenerative rate. If human extraction of an ecosystem's provisioning services exceeds its regenerative rate and that of connected ecosystems, natural capital depreciates. Depreciation caused by pollutants is the difference between the rate at which pollutants are discharged into the biosphere and the rate at which the biosphere can neutralise the pollutants.

2.5 In today's economy, we do not run down the stock of produced capital to the point of depletion because it is widely understood that by doing so, we would reduce the economy's productive capabilities. Quite the contrary, nations accumulate produced capital. Yet we are continually depleting natural capital like

[1] Formally, the accounting price of a capital good is the contribution an additional unit of the good would make to well-being across the generations, other things equal.

estuaries, forests, mangroves, coral reefs, and grasslands, in some cases to the point of reaching their collapse.

2.6 An overarching reason underlying our over-use of the biosphere can be traced to institutional failure writ large. One important manifestation of institutional failure is the presence of *externalities*, which are the unaccounted-for consequences for others, including future people, of our actions. Our use of Nature's services gives rise to a plethora of externalities, including those that arise from the fact that much of Nature is free at source and open to all, limiting incentives to curb our demand. The Review studies the reasons much of the biosphere remains an *open access* resource.

2.7 Environmental degradation and biodiversity loss are experienced differently by people in different roles and in different parts of the world. But we all face asset management problems, every day, in every society, in a wide variety of guises: from individuals to village councils, government departments to businesses, international agencies to private investors. Each agent develops a strategy for managing assets, including natural assets, whether consciously or unconsciously.

## Rates of return on investment

2.8 Biodiversity is not an asset. Rather, it is a descriptive feature of assets we call ecosystems. Drawing an analogy with human institutions, we may say that biodiversity in an ecosystem resembles the extent to which people trust one another in a human society. This is why the building blocks of the economics of biodiversity are *own rates of return* on assets. Formally, the own rate of return on investment in an asset is the increase in the asset's size that would be expected tomorrow if a unit more of the asset were added to a portfolio today. The additional unit is the investment in question. An example would be the additional biomass of a fishery that would be expected tomorrow if the biomass in the fishery were increased by a unit today. A further example would be the increase in a tree's biomass per unit of its biomass if we were to wait a while. Waiting suggests that a natural capital's own rate of return is its regenerative rate for a marginal unit of stock. The Review confirms that this is exactly right. Likewise, the own rate of return on investment in produced capital is its marginal product.

2.9 These contrasting examples suggest that 'investment' has a deeper meaning in the economics of biodiversity than it has in modern growth and development economics. The latter typically asks us to imagine investment as people in hard hats using machines to apply tarmac to a road. In contrast, fisheries and forests grow if left alone. So, investment can be passive. Not only does restoration of natural capital counts as investment, so does conservation: investment can mean simply waiting.[2]

2.10 An own rate of return is a pure number of per unit of time. Its dimension is therefore the inverse of time (i.e. $time^{-1}$). In the case of financial assets, own rates of return are often called their *yield*. An example is the return the UK government offers for its long-term bonds, which has averaged around 4% (or 0.04) a year historically. 4% a year is the yield (Thomas and Dimsdale, 2017).

2.11 When comparing assets in a portfolio, however, own rates of return are not enough. Unless the economy is in a stationary state, assets' relative prices can be

[2] See Solow (1963), whose treatment of own rates of return covered investment in both its active and passive senses.

expected to change over time. So, when comparing the benefits of holding a portfolio, own rates of return on the assets in that portfolio must be corrected for their relative capital gains (or losses). The *rate of return* on an asset (as opposed to the asset's *own* rate of return) is its yield plus the capital gains it enjoys over a unit of time. Portfolio management requires that the household chooses a portfolio with the maximum value among all the portfolios to which it has financial access. Value maximisation should be the household's criterion for portfolio decisions. Of course, yields would typically be uncertain, as would future prices. Value maximisation would reflect the uncertainty and the household's attitude toward risk and uncertainty. The Review elaborates on the idea of value maximisation as it applies to the economics of biodiversity.

2.12 It is a commonplace understanding in financial economics that asset management involves comparing rates of return on alternative portfolios. Assets in an efficient portfolio yield the same rate of return, as estimated by the decision maker (corrected, of course, for risk). A portfolio is efficient *only* if the assets in it have the same rate of return, again, corrected for risk.

2.13 Box 2.A shows by means of an illustrative example that the own rate of return on the biosphere far exceeds the average return on produced capital. But as most of Nature's worth to society is not reflected in market prices, the private rate of return for investment in most of Nature remains low, even zero. These pricing distortions mean we have been investing relatively more in other assets, like produced capital. Simple though it is, the example highlights the significant *under*-investment in Nature.

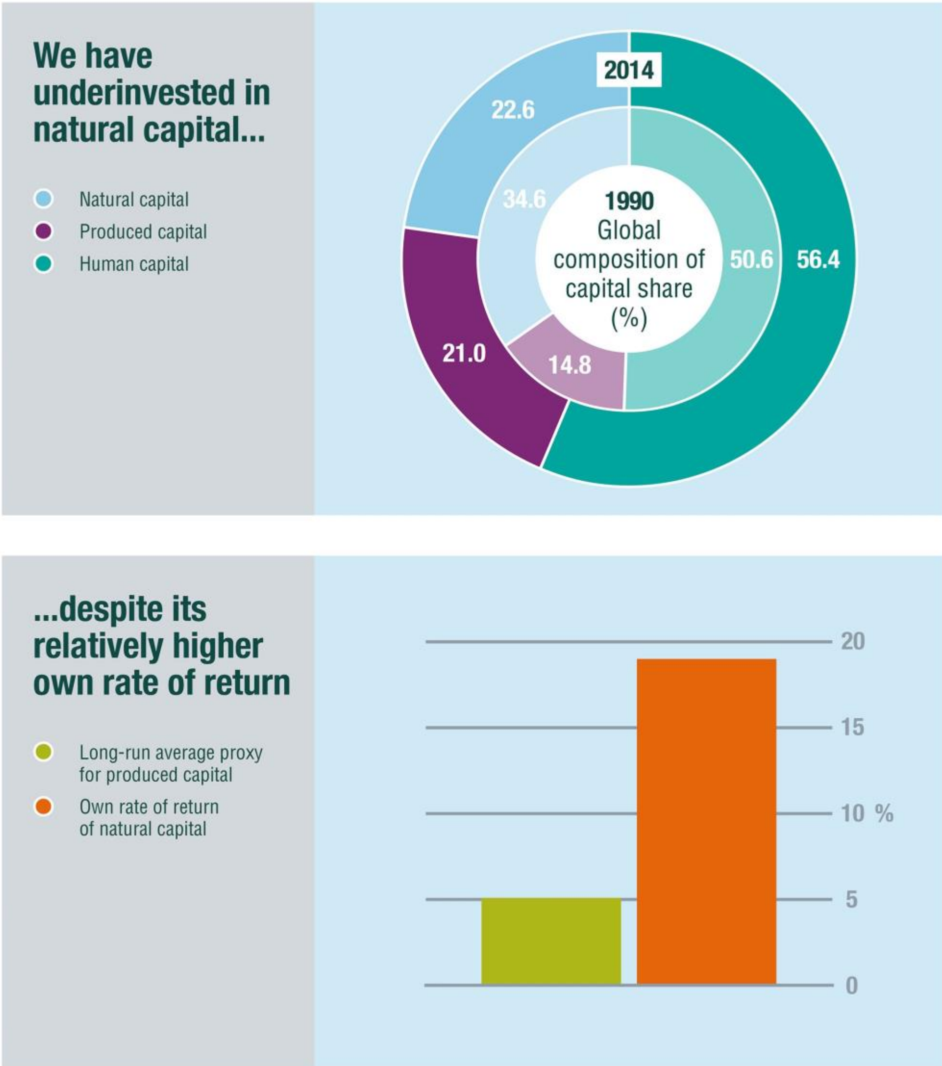
### Box 2.A: Globally Inefficient Management of our Portfolio of Assets

The significance of rates of return in portfolio asset management can be illustrated with a simple illustrative exercise. Using remote sensing techniques, Planetary NPP at the end of the 20th century was estimated to be around 105 trillion kg per year (Christopher B. Field et al., 1998). A similar approach was used to estimate the global stock of live biomass, which is around 550 trillion kg (Yinon M. Bar-On, Phillips and Milo, 2018). It follows that the biosphere-wide average own rate of return (105/550 a year) is around 19% a year.

When compared to the own rate of return on produced capital – proxied by the long-run global yield (rent or dividend) on housing and equities, which has averaged around 5% (Jorda et al., 2019) – the own rate of return on planetary biomass is significantly higher. If the global portfolio was deemed to be efficient, we would expect capital losses on the biosphere equal to the difference between these rates of return (i.e. around 14% a year). But the global economy has been decumulating natural capital while accumulating produced capital. That means the accounting price of the biosphere relative to that of produced capital will have been *increasing*, which means that Nature should be enjoying 'capital gains' against produced capital, not capital losses! That shows humanity has been mismanaging the global portfolio of assets.

The underlying problem is that much of the biosphere is open to all at no monetary charge; so Nature's worth to society – their accounting prices – are not reflected in market prices. The *private* rate of return on investment in many forms of natural capital remains low, even zero. These pricing distortions mean we are investing relatively more in other assets (Figure 2.A), such as produced capital, that yield lower social rates of return. This example highlights the staggering mismatch between private incentives and societal needs.

Figure 2.A: Rates of Return




*Note: Graphic of rates of return on capital. Source: Data from C.B. Field et al., 1998; Managi and Kumar, 2018; Yinon M Bar-On, Phillips and Milo, 2018; Jorda et al., 2019.*

2.14 The Review argues that we must manage our asset portfolios better from two perspectives. First, we should manage our overall stock of all capital assets more efficiently by reversing the recent depletion of natural capital. Second, we should maintain biodiversity in our portfolio of natural capital.

2.15 To elaborate on the latter point, biodiversity plays a similar role in the natural world to diversity in financial portfolios: it reduces variability and uncertainty in yield. The variability of species in the system and the genetic variation within those species enables the ecosystem to respond to change, acting as a form of insurance or as a diverse portfolio that spreads risk.[3] If a species is lost, there may be another that could fulfil its role in an ecosystem, like 'the bench' of substitutes in a sports team. As more species are lost, it becomes less likely that other species will be present to fill their roles. Some species are so critical to the functioning of an ecosystem (known as *keystone species*), that their loss alone can cause an ecosystem to move into a new state. The loss of sea otters in the North Pacific Ocean, for example, led to a rise in sea urchins who then consumed vast quantities of kelp, destroying breeding habitats for many fish (Estes and Palmisano, 1974).

2.16 Biodiversity also provides ecosystems with sources of complementary functions and has positive effects on an ecosystem's productivity. In this way, biodiversity is akin to complementarities among inputs in economic production. Soil biodiversity provides an example: different groups of organisms act to maintain soil health in different ways. Archaea, bacteria, and fungi act as chemical engineers, decomposing plant residues and soil organic matter, contributing to nutrient transitions and recovery of polluted soils. Other microorganisms act as biological regulators, controlling plant pathogens and contributing to food security. Larger organisms, such as earthworms, termites, and small mammals, act as ecosystem engineers, controlling the structure of the soil matrix. Without these diverse species playing different roles, soil would fail to support the global food system (Orgiazzi et al., 2016; FAO, 2019).

## The world in the Anthropocene

### The Best of Times

2.17 How did we arrive at such an imbalance in humanity's portfolio of assets? Since the middle of the previous century, humanity as a whole has prospered at an unprecedented rate. The average person today enjoys a far higher income and lives years longer than then. Global output of final goods and services in 2011 prices has risen from around 9 trillion international dollars[4] in 1950 to over 120 trillion today – a more than 13-fold increase in just 70 years – while the average person's annual income has risen from 3,500 dollars in 1950 to 17,000 dollars (Dasgupta and Dasgupta, 2017; Barrett et al., 2020). Over the same time period, global life expectancy at birth has risen from 49 years to nearly 73 years (UN Population Division, 2019), and the proportion of the world's population in absolute poverty (living on less than 1.90 dollars a day) has fallen dramatically, from nearly 60% in 1970 to less than 10% today (World Bank, 2018).[5]

2.18 These achievements have been celebrated in a string of widely noted publications.[6] Aside from climate change though, the authors had little to say about the state of the biosphere today and the direction in which it has been moving in recent decades. That humanity has "never had it so good" is incontrovertible. But the exercises in these publications focused on the present in comparison to the past. The scale of human activity that we have reached tells us that we should look also at

---

3 The insurance value of biodiversity was investigated in a wide-ranging series of field experiments by David Tilman (see e.g. Tilman, Isbell and Cowles, 2014).

4 International dollars at Purchasing Power Parity or PPP. All subsequent figures are at PPP.

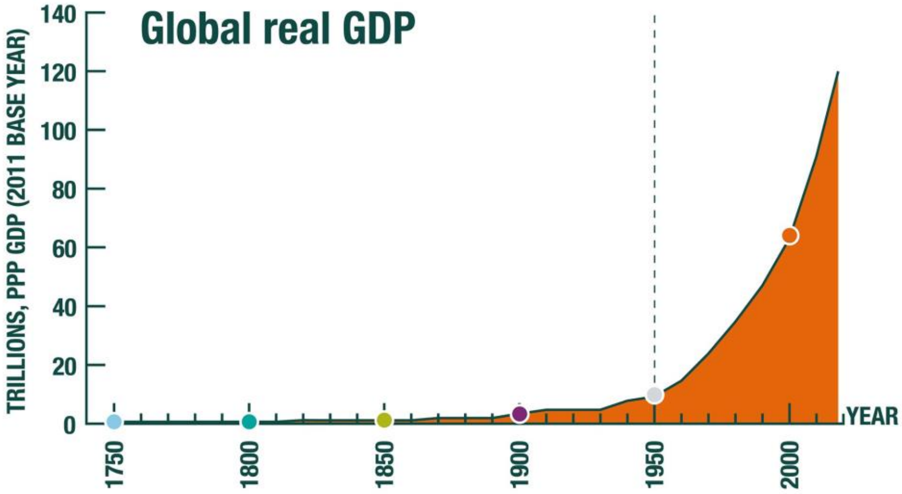
5 We are speaking to aggregate figures. The Review also looks at links between the distribution of income and wealth and biodiversity loss at the local level.

6 Wooldridge and Micklethwait, (2001), Ridley, (2012), Lomborg, (2013), Norberg, (2016) and Pinker (2018).

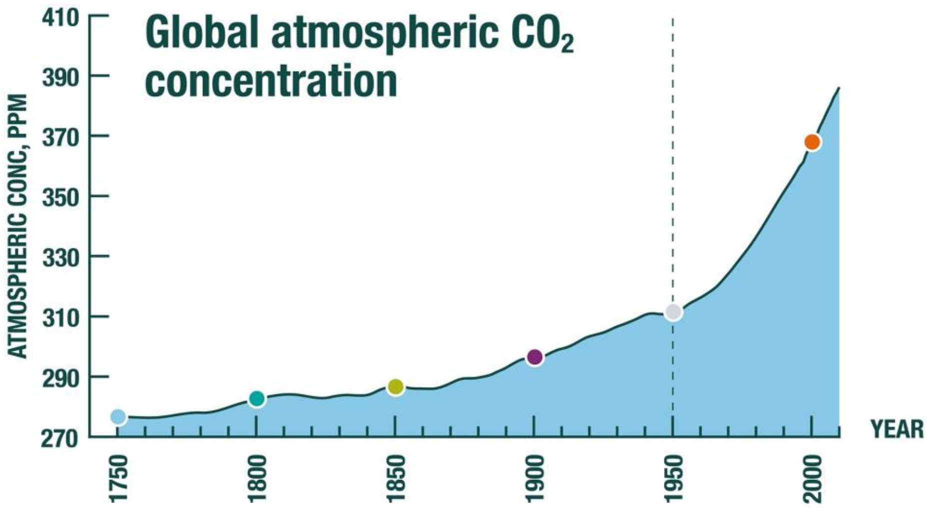
the current symptoms of the biosphere, for they tell us something about future prospects.

2.19 Earth scientists have named the new age we have entered 'the Anthropocene', in which human activity has become the dominant influence on the biosphere (Ehrlich and Ehrlich, 2008). Figure 2.B displays time series of real global GDP and global carbon dioxide emissions since the start of the industrial revolution. In the middle of the last century there was a sharp accelerated rise in global production of both final goods and services and carbon emissions. This raises the question of how the biosphere has been changing.

Figure 2.B: Global real GDP and global atmospheric carbon dioxide ($CO_2$) concentrations since 1750




*Note: Graph of global real GDP. Source: Our World in Data based on World Bank and Maddison (2017), Maddison Project Database, version 2018. Bolt, Jutta, Robert Inklaar, Herman de Jong and Jan Luiten van Zanden (2018), "Rebasing 'Maddison': new income comparisons and the shape of long-run economic development", Maddison Project Working paper 10.*




*Note: Graph of global atmospheric carbon dioxide concentration. Source: D. Etheridge CSIRO, Australia; Etheridge et al., 1996, MacFarling Meure et al. 2004 and 2006, Langenfelds et al. 2011.*

## The Worst of Times

2.20 Our growing prosperity has come at a cost: our demands for the biosphere's goods and services have overshot its capacity to supply them on a sustainable basis. The biosphere responds to the demands we make of it by undergoing changes. If our aggregate demand exceeds its regenerative rate, the biosphere diminishes, in quantity or quality or both. By contrast, if our demand is less than its regenerative rate, the biosphere improves in health. Our overall demand on the biosphere is sustainable over the long run *only if* it is less than or equal to the biosphere's regenerative rate.

2.21 The demands we make of the biosphere take two forms:

2.22 First, we draw upon Nature's goods and services as inputs for consumption and production. This includes provisioning services like fish, fibre and freshwater as well as regulating and maintenance services like pollination, flood protection, and water purification.

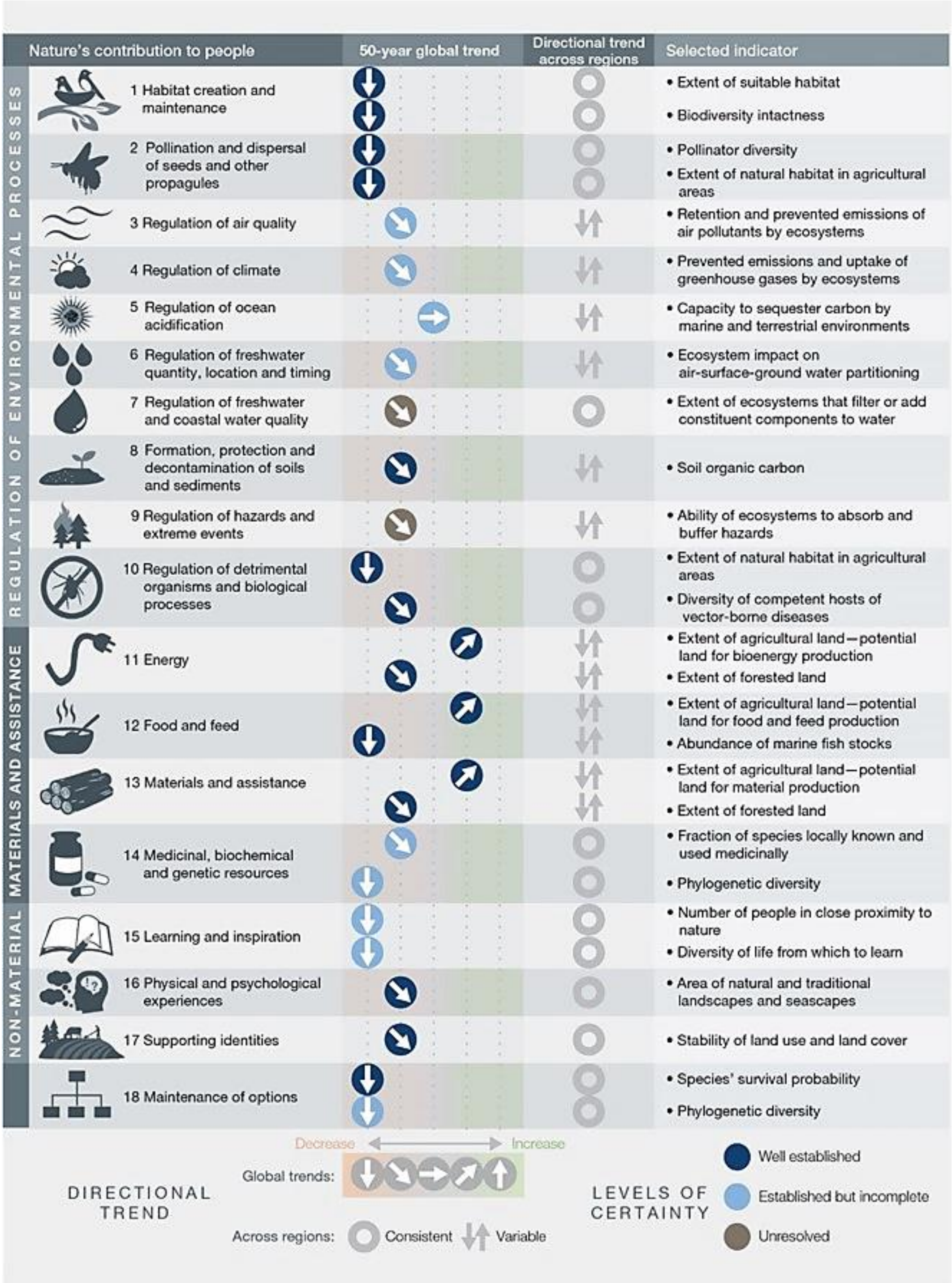
2.23 Second, we use the biosphere as a sink for our waste products, for example by putting our rubbish into landfills, pollutants into rivers, estuaries and oceans, and greenhouse gases into the atmosphere. Waste products are inevitably associated with production and consumption and they impose a strain on the biosphere – they impede its ability to function and produce goods and services. In economic terms, they cause the biosphere to depreciate.

2.24 We noted previously, using crude calculations, that the own rate of return on the biosphere far exceeds rates of return on produced capital. The finding points to a serious imbalance in humanity's portfolio of assets, in which we are running down our natural assets. Below we look more closely at this imbalance. The Review finds that over recent decades our aggregate demand from the biosphere has exceeded the biosphere's ability to meet that demand on a sustainable basis. Four types of evidence are presented here:

### 1. Biodiversity and Ecosystem Service Losses

2.25 Running in parallel with the rising prosperity that humanity has enjoyed over the past seven decades, there have been profound losses in biodiversity across continents and biomes, and dramatic changes in the biosphere. That diminution was reported in the Millennium Ecosystem Assessment (2005), which found that 15 of 24 ecosystem services assessed were in decline. The recent IPBES global assessment reported a decline in 14 of 18 categories of nature's contributions to people since 1970 (IPBES, 2019). Both global reviews found that extraction of provisioning services has increased, while provision of regulating and maintenance services has declined. There is evidence too of a corresponding decline in cultural services. Figure 2.C shows the overall trends in Nature's contributions to people reported by IPBES.

## Figure 2.C: Global trends in the capacity of nature to sustain contributions to good quality of life from 1970 to the present



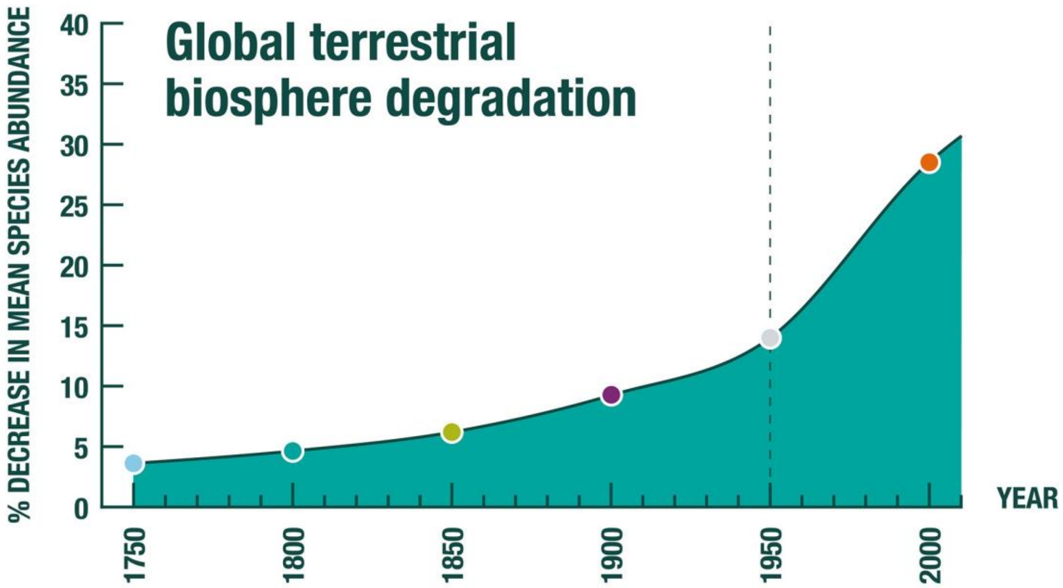

*Note: Graphic of global trends in Nature's contribution to people. Source: IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES Secretariat.*

2.26 The decline in regulating and maintenance services, as well as cultural services, can be traced to the enormous growth in the extraction of provisioning services. The Review explains that reasoning.

2.27 The prime driver behind these transformations has been the conversion of habitats for production of provisioning services, industrial activity, and human habitation. Changes in land and sea-use and over harvesting have been found to be important drivers of biodiversity loss, as well as climate change, invasive alien species, and pollution of air, water, and soil (Perrings, 2014; IPBES, 2019).

2.28 Although biodiversity is a broader and more complex notion than species diversity, it should come as little surprise that there is ongoing extinction of species. Extinction rates are currently 100 to 1,000 times higher than the average over the past several million years, and the rates themselves are accelerating (Pimm et al., 2014; De Vos et al., 2015; Pimm and Raven, 2019). The Living Planet Index shows an over 60% decline in populations of mammals, birds, fish, reptiles and amphibians over the past four decades, with declines across biome and region (WWF, 2018). The estimated number of wild bee species worldwide has fallen from 6,700 in the 1950s to only 3,400 in the 2010s (Law, 2020). IPBES reported that one million animal and plant species are now threatened with extinction, many within decades (IPBES, 2019). This is illustrated in Figure 2.D, which shows the decrease in mean species abundance as a proxy measure of degradation of the terrestrial part of the biosphere.

Figure 2.D: Changes in global terrestrial biosphere degradation since 1750

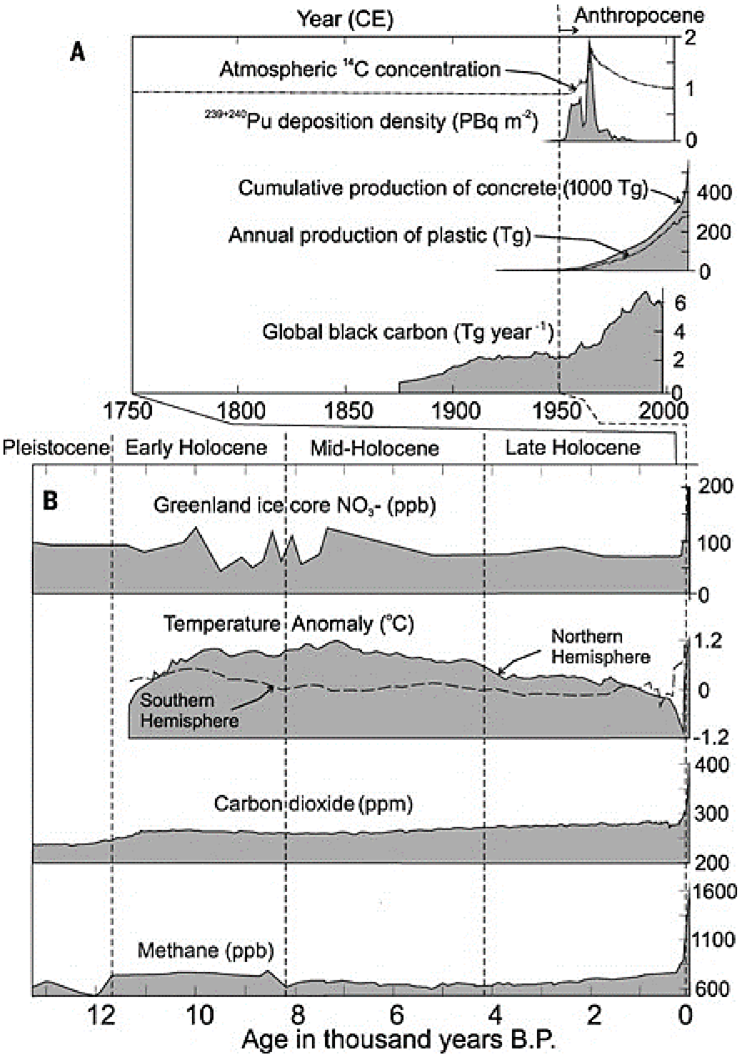



*Note: Graph of change in species abundance. Source: Steffen, W. et al. (2011) 'The anthropocene: Conceptual and historical perspectives', Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369(1938), pp. 842–867.*

## 2. Biogeochemical Signatures

2.29 Strikingly, Waters et al. (2016) reported that the dramatic changes in the state of the biosphere in recent decades are also evident in global biogeochemical 'signatures' of soil nitrogen, phosphorous and other markers, in sediments and ice over the past 11,000 years. The authors found that their time series were flat for millennia until a slow rise about 250 years ago, followed by a dramatic increase since 1950 (Figure 2.E). This is why Earth scientists have identified the immediate post-War years as the time we entered the Anthropocene (Voosen, 2016).

## Figure 2.E: Summary of the magnitude of key markers of anthropogenic change indicative of the Anthropocene




*Note: Graphs of key markers of anthropogenic change. Source: Waters, Colin N et al. (2016) 'The Anthropocene is functionally and stratigraphically distinct from the Holocene', Science, 351(6269), pp. aad2622–aad2622. Permission to reproduce from AAAS.*

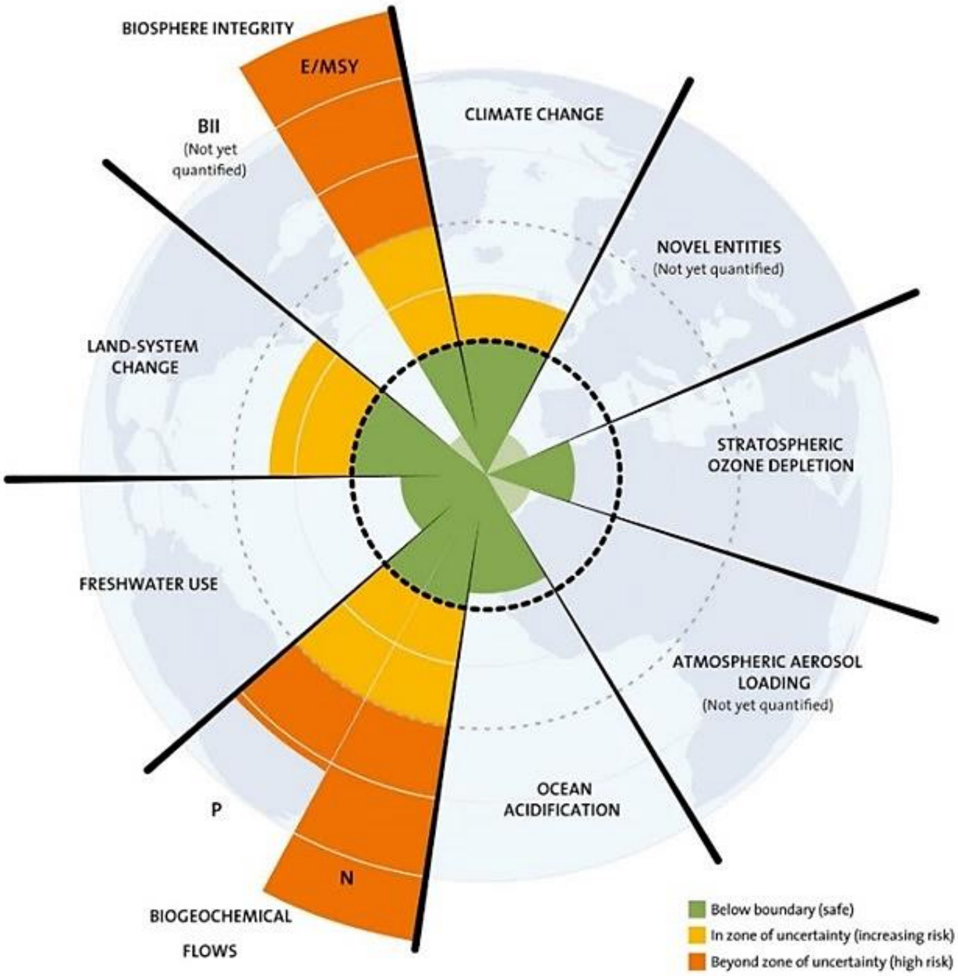
## 3. Safe Distance from Planetary Boundaries

2.30 Further evidence of the biosphere's degradation is adduced from earth system processes. Work has been undertaken to identify biospheric processes that are critical for maintaining the stable state we experienced during the last approximately 11,000 years, the age called the *Holocene*.[7] Markers that signal that the processes are undergoing rapid change have been called *planetary boundaries* (Rockström et al., 2009). Although not all these processes have single identifiable markers, crossing the boundaries increases the risk of large-scale, potentially irreversible, environmental changes. The authors identified nine planetary boundaries, of which climate change and 'biosphere integrity' were deemed to be

[7] The approach defines nine processes critical for Earth System functioning, and attempts to set quantitative biophysical boundaries for each, beyond which the Earth's Holocene state is put at risk. A planetary boundary is not equivalent to a global threshold or tipping point: 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.

‘core’ boundaries, to which the other seven relate. Two among the nine processes have taken the planet into regions that scientists regard as outside ‘safe operating space’, meaning that there are now increasing risks of significant changes from the biosphere’s conditions in the Holocene (Steffen et al., 2015; Steffen et al., 2018). The biosphere’s integrity and nitrogen and phosphorous cycles have exceeded their boundaries furthest. But land use change and climate change are also outside their safe operating space (Figure 2.F).

Figure 2.F: Critical earth system processes and their boundaries




P = phosphorus; N = nitrogen; BII = Biodiversity Intactness Index and E/MSY = extinctions per million species per year.

*Note: Diagram of critical earth system processes. Source: J. Lokrantz/Azote based on Steffen, W. et al. (2015) ‘Planetary boundaries: Guiding human development on a changing planet’, Science, 347(6223), pp. 1–10.*

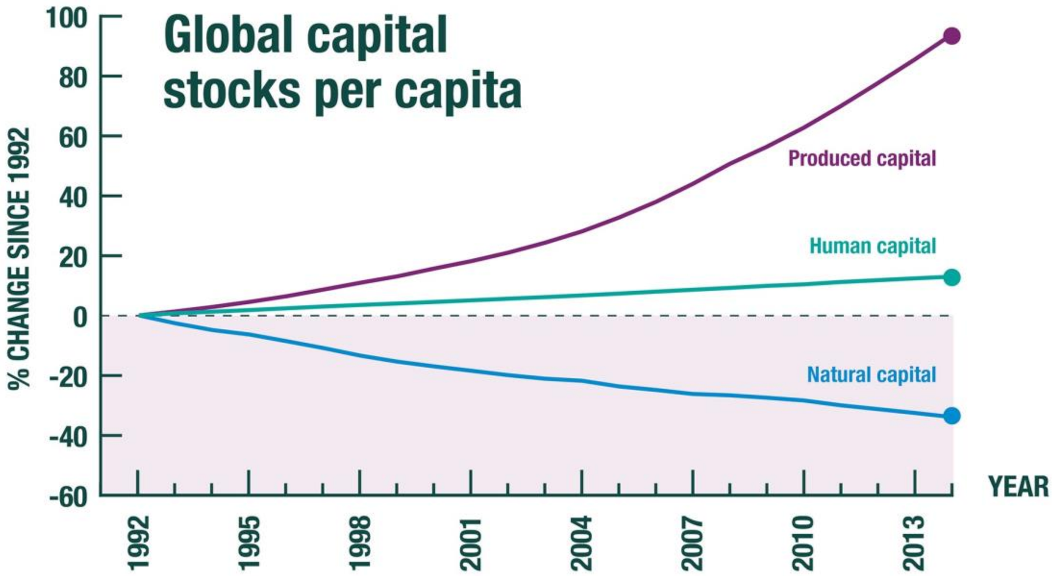
## 4. Global Natural Capital Accounts

2.31 Global capital accounts also reveal the way we are depleting the biosphere. Managi and Kumar (2018) have tracked produced capital, human capital and natural capital over the period 1992-2014 in 140 countries.[8] Figure 2.G displays the

8 The value of produced capital was obtained from official national accounts. Data limitations meant that natural capital 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 was estimated by using the approximations in Arrow et al. (2012) for both education and health.

authors' estimates of global per capita accounting values of the three classes of capital goods over the period 1992-2014. 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 2.G: Global changes in human, produced and natural capital per capita




*Note: Graph of changes in global capital stocks. Source: Managi, S. and Kumar, P. (2018) Inclusive Wealth Report 2018. London.*

## The Impact Inequality and sustainable development

2.32 To sustain our natural assets, our demands on Nature must be equal to, or less than, its regenerative rate.

### Our demands on the biosphere

2.33 The Review calls humanity's impact on the biosphere per unit of time the *global ecological footprint*. To construct a measure of that impact, the Review uses $N$ to denote human population and $y$ an index of human activity per person per unit of time.[9] Estimating average human activity per person is challenging. For tractability, the Review assumes it corresponds to the standard of living, as measured by GDP per capita. This assumption likely yields an underestimate, because there are many human activities that are not captured in the market value of all final consumption of goods and services.[10] Global output of final goods and services is therefore only a proxy for human activity.

2.34 Degradation of the biosphere can hasten the depreciation of other assets (rising sea level submerges coastal infrastructure (produced capital), hotter weather lowers labour productivity (human capital), and so on). Here we do not focus on

9 Here we follow the formulation of Ehrlich and Holdren (1971) of humanity's impact on the biosphere.

10 There have been initiatives by national income statisticians to estimate the magnitude of economic transactions that are missing in GDP. They are not included here, however, given the early stage of their development.

interactions among capital assets, but instead on the demand we make of the biosphere's goods and services specifically. For simplicity, we combine the two forms of demand we make of the biosphere – for its goods and services and as a sink for our waste. We use X to denote global demand, which is a function of human population and human activity per person, i.e. $X = X(Ny)$.

2.35 We use $\alpha$ to denote a numerical measure of the efficiency with which the biosphere's goods and services are converted into GDP. $Ny/\alpha$ is therefore a proxy measure of the global ecological footprint.[11] If the footprint exceeds the biosphere's regenerative rate, the stock diminishes. Conversely, if the footprint is less than the biosphere's regenerative rate, the stock increases. However, either population or the output of final goods and services per capita, or both, could increase without making additional demands on the biosphere *provided* $\alpha$ increased correspondingly. Improvements in technology (for example, substituting degradable waste for persistent pollutants, or decarbonizing the energy sector) and institutions and practices (for example, establishing protected areas, or reducing food waste), and appropriate redistributions of wealth are among the means by which $\alpha$ can be raised.

2.36 Economics and ecology taken together show that there are limits to which $\alpha$ can be increased so as to reduce humanity's ecological footprint, which means attention should also be directed at those two neglected factors in environmental and resource economics: the human population (N) and global output per person (y) (see Boxes 2.B and 2.D, which respectively explore demographic and consumption trends in more detail, and what drives consumption practices and fertility behaviour).

## Planetary supply: the biosphere's regenerative rate

2.37 To represent the biosphere's supply of goods and services, we develop a supply function. G denotes the regenerative rate of the biosphere. G depends on the biosphere's stock, denoted as S. Thus $G = G(S)$. The *G*-function can also be affected by policy. The application of biotechnology in agriculture is one avenue to increase the regenerative rate. Another is *ecosystem engineering*. For example, transplanted heat-tolerant corals have been found to be more likely to survive a bleaching event than less tolerant local corals, enabling quicker recovery of the ecosystem after such an event (Morikawa and Palumbi, 2019). In the range of stocks relevant to our current situation (stocks below the level capable of sustaining a maximum yield), it is reasonable to assume that if S were to increase, G(S) would rise.

## Demand and Supply

2.38 Humanity's ecological footprint does not have to equal the biosphere's regenerative rate. That is because the difference would automatically be 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. But this scenario comes in tandem with an overshoot in our demands on the

---

[11] Decomposition of the global ecological footprint when the footprint is interpreted as global carbon emissions is known as the Kaya Identity. See Kaya and Yokobori, (1997).

biosphere. The overshoot cannot, however, be maintained indefinitely because our life support system would be threatened.

2.39 In recent decades, the global ecological footprint ($Ny/\alpha$) has exceeded the regenerative rate of the biosphere (G). As a result, and as noted above, the stock of the biosphere (S) is being drawn down. Formally, we have $Ny/\alpha > G(S)$. As S declines with rising $Ny/\alpha$, G(S) declines, increasing the gap between demand and supply.

2.40 In the language of the Review, Wackernagel and Beyers (2019) define the global ecological footprint as the ratio of demand to supply, that is, $[Ny/\alpha]/G(S)$. The authors estimate that the ratio of demand to supply has been increasing since the 1960s (their data go back to that period), from 0.9 in the late 1960s to 1.7 in 2016, which they express vividly as the need for 1.7 Earths to meet our current demand on a sustainable basis.[12] These estimates reconfirm that in the post-War period, humanity has been drawing down the biosphere, to dangerously unsustainable levels today.[13]

2.41 The global ecological footprint ($Ny/\alpha$) is bounded because the biosphere's regenerative rate (G) is bounded. That means unending growth in GDP per capita (y) would require $\alpha$ to grow at least at the same rate.[14] But to raise $\alpha$ requires investment, for example in research and development. It follows that if $\alpha$ is to keep step with y no matter how large y is imagined to be, investment in further increases in $\alpha$ would require, at the margin, vanishing contributions from the biosphere. That requires us to imagine that, in the long run, we can be free of the biosphere for any further investment. The Review concludes that $\alpha$ must therefore be bounded above. It follows that y must be bounded above too. This conclusion is in sharp contrast to the assumptions underlying contemporary growth and development economics, and by extension the economics of climate change. Whereas that literature sees humanity as external to the biosphere, the Review sees us embedded in it. We elaborate on that below.

2.42 The Review calls $Ny/\alpha > G(S)$ the *Impact Inequality*, illustrated in Figure 2.H.[15] The Impact Inequality identifies the three key factors underlying our demands on the biosphere: human population numbers, global GDP per person, and the efficiency with which we convert the biosphere's goods and services into GDP. International and national policies should be geared towards converting the Impact Inequality into an *Impact Equality* – that is, bringing about equality between $Ny/\alpha$ and G(S), and that too at a healthy state (S) of the biosphere. That should be what 'sustainable development' is taken to mean.[16]

---

12 In order to provide that vivid description, Wackernagel and Beyers assume that G(S) is a linear function.

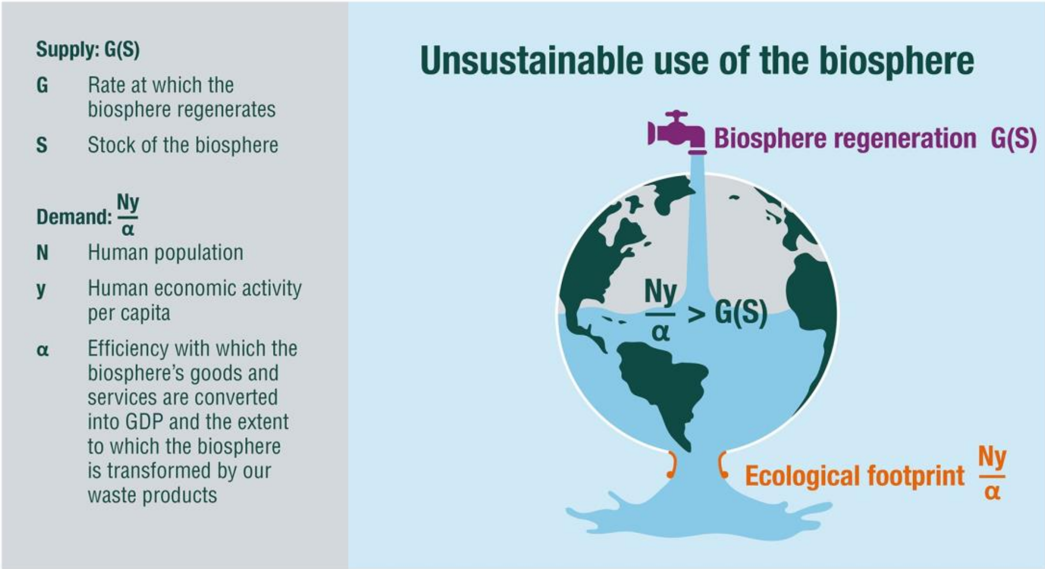
13 The biosphere is bounded. The Review explains why in consequence G is not an ever-increasing function of S. As the estimates of the biosphere's own rate of return in Box 2.A confirm, the biosphere is at a state in which G is an increasing function of S. But if S were to be very large, G would decline with further increases in S. Fisheries and forests are examples of the idea: G increases with S when S is small but declines with S when S is large. We are currently below a figure for S at which G(S) is below its maximum sustainable level.

14 The Review assumes no one imagines Earth to support an indefinitely growing N.

15 The left hand side of the Impact Inequality is what Ehrlich and Holdren (1971), in their pioneering paper, called human 'Impact' on the biosphere. For furthering unravelling of the Impact side of the inequality, see Barrett et al. (2020).

16 Annex C provides a formal mathematical exposition of the Impact Inequality.

Figure 2.H: The Impact Inequality

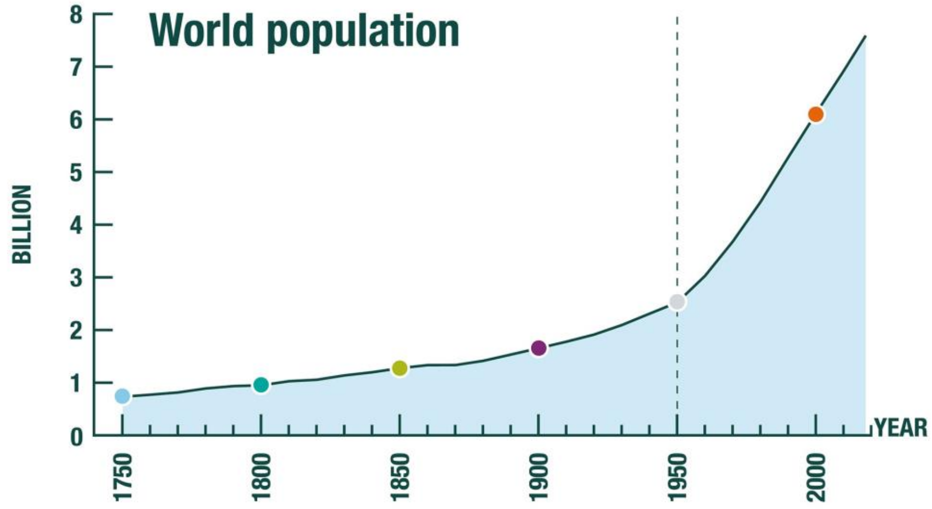



*Note: Graphic of the Impact Inequality.*

### Box 2.B: Demographic and consumption trends

The world as a whole and most regions and countries are experiencing unprecedented and rapid demographic change. The most obvious example of this change is the significant expansion of human numbers: the global population trebled in size from approximately 2.5 billion in 1950 to around 7.7 billion in 2019 (see Figure 2.I). The UN's median projection of world population in year 2100 is 10.9 billion, with a 95% certainty range of between 9.4 billion and 12.7 billion (UN Population Division, 2019).

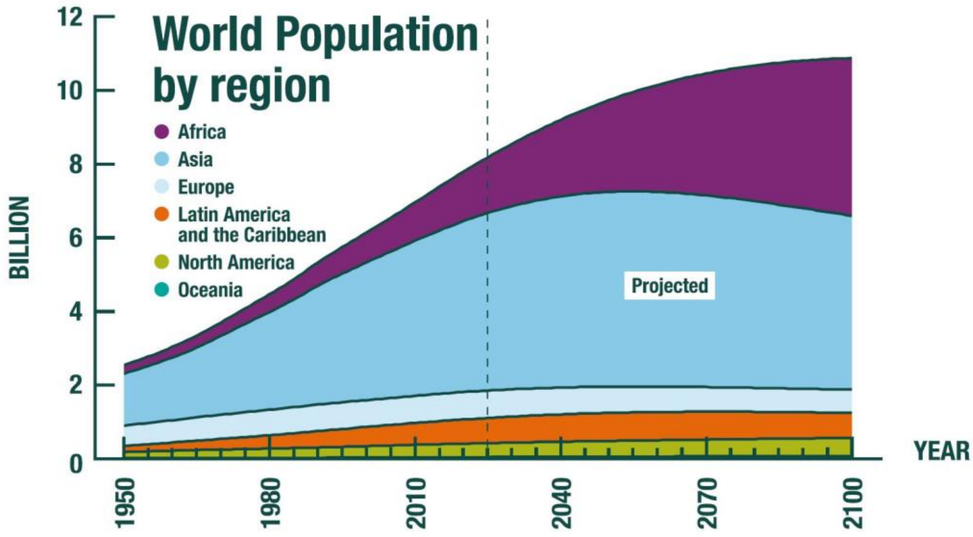
#### Figure 2.I: World Population




*Note: Graph of the change in world population since 1750. Source: UN Population Division (2019).*

Projections for the next half century expect a highly divergent world, with stagnation or potential population decline in parts of the developed world and continued rapid growth in many developing countries (Figure 2.J). More than three-quarters of the increase from today's 7.7 billion is expected to be in sub-Saharan Africa, where population in 2100 is projected to rise from approximately 1.1 billion in 2019 to 3.8 billion.

Figure 2.J: Total population by region with projections, 1950 to 2100




*Note: Graph of the change in total population by region, 1950 70 2100. Source: UN Population Division (2019a).*

Comprising around 14% of the world's population, sub-Saharan Africa represents around 3% of the world economy. So sub-Saharan Africa cannot remotely be held responsible for the global environmental problems we face today. However, raising incomes there even to the current global average income (approximately 17,000 international dollars) in the face of a near-3 billion rise in numbers will require an increase in the region's annual output from 3.5 trillion international dollars to about 68 trillion international dollars at today's prices. That rise, assuming that it is achievable, is all too likely to have enormously adverse consequences for the region's ecology (Barrett et al., 2020).

These demographic changes have significant implications for the future pattern of global consumption, meaning that y is not independent of N. The World Bank (2017) has reported that the 1.2 billion people on its list of high-income countries enjoy a per capita GDP (constant prices) of around 45,000 international dollars, implying a GDP of around 54 trillion international dollars. World output today is around 120 trillion international dollars. There is evidence that 'carbon footprint' is proportional to the scale of economic activity. If we assume in the absence of firm evidence or otherwise that the linear relationship holds for ecological footprint also, a little below 50% of humanity's impact (US$54 trillion/US$120 trillion) on the biosphere can be attributed to some 16% of the world's population. If we assume also that global output grows at such a rate that per capita global output in year 2100 will be, at today's prices, 30,000 international dollars (which is around the 75th percentile on the distribution of GDP per capita across countries at present) then global output at a population size of 10.9 billion would be 336 trillion international dollars. Unless the efficiency in our use of the biosphere (α) increases correspondingly, it is not hard to imagine what the biosphere's response would be.

The Review uses estimates of the global ecological footprint since the 1960s to project how fast $\alpha$ must grow if the UN's Sustainable Development Goals (SDGs) are to be met in terms of sustainable use of the environment (in particular SDGs 14 and 15) by year 2030 if current projections of global GDP are realised (see Box 2.C). The Review also studies ways in which future population numbers (N) and our material demands (y) can be influenced in order to reduce the gap between the biospheric demand and supply.

Other demographic processes are also undergoing extraordinary change. Past trends in fertility and mortality have led to very young populations in high fertility countries in the developing world and to increasingly older populations in the developed world. Contemporary societies are now at very different stages of their demographic transitions. However, that there will be in all likelihood demographic transitions in all societies is a misleading sign of hope: the Impact Inequality makes clear that Nature does not respond to rates of change in our demands, it responds to the level of our demands. It is all too possible that by the time all regions of the world experience demographic transitions, the biosphere will have been damaged so badly that large parts are beyond repair in the time frame of the human population.

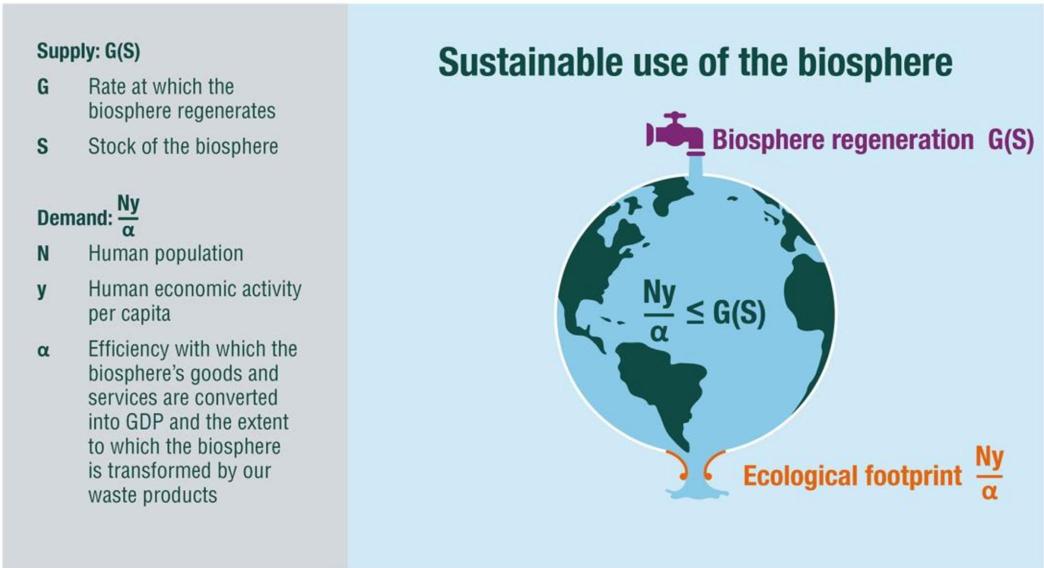
One sign of hope that both consumption and future population numbers can be reduced without undue burden to us is a feature of human preferences that has been overlooked in macroeconomic thinking, including the economics of climate change. Contemporary growth and development economics including the economics of climate change imagines the human person to be an *egoist*. An enormous empirical literature in anthropology and sociology has, in contrast, shown that the individual is embedded in society (see e.g. Barrett et al., 2020). We look to others when making decisions. In some areas of decision-making we compete, in some others we conform. A shared reduction of a unit of consumption by each individual is less costly to a person than if a reduction of one unit of consumption fell solely on him. The same preference trait shapes fertility behaviour (Dasgupta and Dasgupta, 2017). The Review develops this line of enquiry and shows how public policies can make use of the fact that our preferences are 'socially embedded.' The human costs of reductions in y and future N are likely to be far less than is imagined (see Box 2.D).

2.43 The Impact Equality is only a condition for sustainability *globally*, in other words for the whole biosphere. Demands on local ecosystems also need to be within their regenerative rates. Trade in commodities and services breaks the link between demand and supply for smaller scales, as it allows demand in one location to be separated from the location of its environmental consequences. The Review will consider how trade affects the global ecological footprint overall and how it can affect the distribution of wealth when the accounting prices of Nature's services are not reflected in market prices. For example, a redistribution of wealth occurs when developing countries export primary products – like timber or crops – to developed countries at prices that do not reflect their social scarcity values, particularly when the production degrades local ecosystems, with consequences for a range of local ecosystem services.

2.44 The requirement for a state of affairs to be sustainable is that it can persist indefinitely. As noted, the Impact Equality is a condition of global sustainability in our engagements with Nature (illustrated in Figure 2.K). Box 2.C shows what is required of our efficiency (α) to achieve sustainability in terms of the Impact Inequality by 2030, the time frame of the UN SDGs, under business as usual in terms of GDP growth.

2.45 But as there is an entire range of values of the biosphere's stock (S) for which the Impact Equality holds, the equation does not identify the level of S we should seek to attain. Identifying the desired stock is critical for setting biodiversity and environmental targets. To do that, a language for policy analysis is needed.[17] We return to this at the end of this chapter.

Figure 2.K: The Impact Equality: The condition for global sustainability




*Note: Graphic of the Impact Equality.*

[17] For the key factors in the Impact Inequality, which are S and corresponding sets of values of the remaining factors, N, y, α, and parameters of the G-function.

## Box 2.C: Reaching the UN Sustainable Development Goals

The Impact Inequality offers a way to discover the proximate factors that must be influenced by policy and behavioural change if the global economy is to meet the UN SDGs. To illustrate, consider the SDGs which call for sustainable use of the oceans and terrestrial ecosystems by 2030.[18]

We have defined the global ecological footprint as 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 on a sustainable basis, which we interpret here as G. The GFN's global ecological footprint is then [Ny/α]/G. Wackernagel and Beyers (2019) report that the ratio increased from a value of 1 in 1970 to 1.7 in 2019. That means the ratio increased at an average annual rate of 1.2%. Furthermore, since 1970, global GDP at constant prices has increased 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) have estimated that the value of per capita natural capital globally declined by 40% during 1992-2014. That converts into an annual percentage rate of decline of 1.5%. World population grew at an annual rate of approximately 1.2%. That implies that the value of natural capital globally has declined annually at the percentage rate 0.3%.[19]

The estimates for annual percentage changes in Ny, G, and [Ny/α]/G, enable us to calculate that α has been increasing in recent decades at 2.5% annually. Suppose we want to reach Impact Equality in 2030. That would require [Ny/α]/G to shrink from its current value of 1.7 to 1 in 10 years' time, which means it must *decline* at an annual rate of 5.4%. Assuming global GDP continues to grow at 3.4% annually (notwithstanding the impact of COVID-19 on the global economy) and G continues to decline at 0.3% (i.e. business remains as usual), how fast must α rise?

To calculate this, we write as g(X) the percentage rate of change in any arbitrary variable X. We then have

$$g([Ny/\alpha]/G = g(Ny) - g(\alpha) - g(G) \qquad (1)$$

Equation (1) can be re-arranged as

$$g(\alpha) = g(Ny) - g([Ny/\alpha]/G) - g(G) \qquad (2)$$

[18] Goal 15 (Life on Land) is to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. Goal 14 (Life below Water) is to conserve and sustainably use the oceans, seas and marine resources for sustainable development.

[19] The methods deployed by the Global Ecological Footprint Network (Wackernagel and Beyers, 2019) for estimating changes to the biosphere differ from those deployed by Managi and Kumar (2018). Moreover, because the latter publication includes fossil fuels and minerals, we assume that as a rough approximation 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 is necessary due to under investment in the economics of biodiversity. GDP estimates have been refined continually over the decades by thousands of experts, whereas the human footprint on the biosphere is researched only by a relatively small group.

We now place the estimates of the terms on the right-hand side of equation (2) to obtain

$$g(\alpha) = 0.034 + 0.054 + 0.003 = 0.091$$

In short, $\alpha$ must increase at an annual rate of 9.1%. As that is a significant increase from the historic rate of 2.5%, we consider a different scenario. Suppose global output was to remain constant on average from now to year 2030 and the decline in G was to reduce from the current 0.3% a year to zero. What would the required rate of increase in $\alpha$ be?

Using equation (2) we have

$$g(\alpha) = 0.054 = 5.4\%$$

That is still greater than the rate of increase in $\alpha$ in recent decades. It is easy to see that equation (2) can be used to study the implications of other possible scenarios and policy questions with reference to the SDGs.

## The Economics of Climate Change and Biodiversity Loss

2.46 The literature on global climate change is vast and has been enormously influential in shaping the public's understanding of humanity's mismanagement of the biosphere. Almost without exception, the economics of climate change has taken total human economic activity (Ny) as given, focusing instead on raising efficiency ($\alpha$) by decarbonising the economy, removing $CO_2$ from the atmosphere and, on occasion, raising the G-function by geo-engineering. But the reason $CO_2$ concentrations in the atmosphere have increased is not only that decarbonisation and direct carbon removal have been slow, it is also that growth in both GDP per capita and human population have been strong.

2.47 In contrast to climate change, biodiversity loss has received little attention in the social sciences. One possible reason for this is that the problems raised by biodiversity loss do not generally lend themselves to technological solutions. The Review studies ways societies could reduce total human economic activity (Ny) by (i) supplementing women's education and empowerment as drivers of fertility transitions with possibilities in reforming family planning programmes in developing countries, and (ii) using prices and coordinating changes in norms of behaviour so as to alter our consumption patterns toward ones that are less reliant on the biosphere's provisioning services.

2.48 Why has the efficiency with which we convert the biosphere's goods and services into GDP ($\alpha$) not risen more in connection to climate change? One reason is a low rate of innovation and investment in non-fossil fuel energy sources and carbon capture and storage technologies. These low rates, in turn, have been caused by a persistent and pervasive institutional failure, and a failure to achieve collective action in limiting climate change following nearly 30 years of diplomatic effort. The externalities relating to fertility and consumption have other causes and can and should be addressed by other institutions (see Box 2.D). Doing so will not make up for the lack of progress on addressing climate change directly, but it will help to keep the global mean temperature closer to levels advocated for in the international agreements made among countries around the world.

### Box 2.D: Consumption practices and fertility behaviour are socially embedded

We will need to act on all dimensions of the demand side of the Impact Inequality: population, consumption, and efficiency (through technology and institutions). The Review explores how *socially embedded preferences* can make the necessary transitions in population and consumption easier and less costly than expected.

Consumption patterns are driven in part by our private desires, but in part also by our desire to compete with others (reflected in Veblen's famous study of conspicuous consumption of what today many refer to as 'positional goods' (Frank, 1997) and to conform with others (Bourdieu, 1984). In both the competitive and conformist cases our desire to consume goods is significantly influenced by what others around us are consuming and what they aspire to consume. Our underlying aspirations are therefore 'socially embedded'. A study in California found that an additional installation of solar photovoltaic panels increases somewhat the probability of adoption within the same zip code, with the effect being particularly strong at the localised street level (Bollinger and Gillingham, 2012). Yet another randomised field experiment found that social comparison lowered water consumption by nearly 5% (Ferraro and Price, 2013). Institutions have an important role to play in creating the right environment for changing socially embedded consumption patterns. Evidence from changing environments in workplace canteens has shown that altering the proportion of vegetarian options available, and reducing portion sizes, lead to overall decreases in consumption of the most environmentally damaging food products without causing frustration or discomfort among consumers (Hollands et al., 2018; Garnett et al., 2019).

Fertility practices are also not influenced by private desires and wants alone, they are shaped by societal mores too. Reproductive behaviour is 'conformist' when the family size a household desires is positively related to the average family size in the community or, more broadly, in the world that households come into contact with. Conformism gives rise to externalities harbouring multiple social equilibria, just as they do in the case of consumption practices. So long as all others aim at large families, no household will wish to deviate from the practice; if, however, all other households were to restrict their fertility, every household would wish to restrict its fertility. A society can thus get embedded in a self-sustaining mode of behaviour characterized by high fertility and stagnant living standards, even when there is another potentially self-sustaining mode of behaviour that is characterised by low fertility and rising living standards and which is preferred by all (Dasgupta and Dasgupta, 2017).[20]

The notion that fertility behaviour is driven by socially embedded preferences was given support in a study of contraceptive use in rural Kenya, which found

[20] The structure of social interactions arising from conformist preferences are known as coordination games.

that in communities having dense social networks and a poorly developed market economy, a woman would be unlikely to use contraceptive methods if contraception use in her network was low, whereas she would be likely to use such methods if contraception use in her network was high (Kohler, Behrman and Watkins, 2001). Further support has been provided in a recent analysis of contraceptive uptake in Bangladesh (Munshi and Myaux, 2006). The study concerned women living in the same community but belonging to different religious groups. After controlling for individual differences in education, age, wealth, and the like, the study found that a woman's choice to use contraception depended strongly on the predominant choice made by other women in her religious group and was unaffected by the predominant choice made by women belonging to the other group. Nor is the group that influences the individual necessarily her neighbours.

Women in the world's poorest countries lack information about reasoned family planning, nor do they usually have access to family planning methods. This is why one reason for vigorously expanding the content and reach of such programmes today lies in the 53 million women in sub-Saharan Africa who report they want to stop or delay childbearing but are not using any modern method of contraception (UN Population Division, 2019b). And yet family planning is a neglected feature of contemporary public policy. Currently only about 0.6% of overseas development assistance is awarded to it (Grollman et al., 2018). As a precondition for sustainable development, investment in community-based family planning programmes should now be acknowledged as essential (Bongaarts and Sinding, 2011).

## Understanding the biosphere: Ecosystems and non-linearity

2.49 The Impact Inequality points to the levers we have at our disposal to steer the global economy towards sustainable development. But the Inequality has had to be expressed at the global level. The demand side of the Inequality can in principle be estimated for national economies; it is simple enough to define the ecological footprint of even a person. But trade imperfections and environmental externalities mean that no country can bring about impact equality in their own economy. The Review therefore peers closer into the biosphere by examining the biosphere's component parts: ecosystems. There are broad policies that can be applied to any ecosystem currently under threat. The Review distinguishes these policies from those that are necessarily tailored to the particularities of specific ecosystems. The Review does not offer a catalogue of these policies but does identify salient examples that have worked and others that have failed.

2.50 Processes governing ecosystems display a feature of profound importance for the design of policy: they are *non-linear*. As providers of ecosystem services, ecosystems resemble indivisible entities, in that functional traits of healthy ecosystems complement one another. If you divide an ecosystem into parts by creating barriers, the sum of the productivities of the parts will typically be lower than the productivity of the whole, other things equal. This is a reflection of non-linearity.[21] The implications of non-linearity are so far reaching that it would be no exaggeration to say that the economics of biodiversity is about non-linear Earth system processes. For that reason, the Review delves deeply into the technical issues that arise in consequence. Here we illustrate the salience of ecosystem non-linearities using an example of the widespread human practice of fragmenting ecosystems.[22]

## Fragmentation of Ecosystems

2.51 When habitats are fragmented, abrupt boundaries appear between fragmented patches. In a long running study of the Amazon rainforest, Thomas Lovejoy and his collaborators found that, when fragmented, even large fragments of forest area (100 hectares) can lose up to 50% of their species in a dozen years (Laurance et al., 2002). Clearings as narrow as 80 metres have been found to hinder the recolonization of fragments by birds, insects, and tree-dwelling animals (Laurance et al., 2002). Paleo-biologists have found fragmentation of natural habitats to be a reliable early-warning sign of biodiversity loss. Unfortunately, 70% of Earth's remaining forests today are within 1 kilometre of the forest's edge (Haddad et al., 2015). Future losses to natural habitats owing to further extensions of land for agriculture are estimated to increase by nearly 20% by 2050 (Tilman et al., 2001).

2.52 Fences fragment grasslands and prevents seasonal migration by animals. Plantations and mines create further fragmentation, as do linear infrastructure like roads, railways and pipelines, and increases in the number and sizes of towns and cities. More generally, fragmentation can prevent populations from conforming to their behaviour over their life cycle. For example, damming rivers fragments them. The construction of high dams is favoured by national economic planners because they expand irrigation, supply energy, and offer protection against floods. However, they also alter the hydrology of freshwater ecosystems by fragmenting them. Fragmentation obstructs fish migration routes, which are essential for spawning and feeding, and limits dispersal.

2.53 Freshwater habitats cover only 0.8% of Earth's surface, nevertheless one-third of described vertebrates, including approximately 40% of fish species, are found in them. It has been estimated that the approximately 40,000 high dams that currently exist worldwide have altered 50% of the volume of river water, by either regulation of water flow or fragmentation (Barbarossa et al., 2020). The pending construction of some 3,700 more high dams will raise the figure to over 90%.[23] Current measures of fragmentation are highest in the US, Europe, South Africa, India, and China, but increases in fragmentation due to future dams is estimated by the authors to be especially high in the tropics, with declines in the connectivity index of some 20-40% in the Amazon, Niger, Congo, and the Mekong Basin. The Living Planet Index estimates that populations of freshwater species have declined by 83% since 1970, with fragmentation cited as a major threat facing these ecosystems

---

21 See, for example, Loreau et al. (2001), Worm et al. (2006), and Sodhi, Brook, and Bradshaw (2009).

22 In an extensive study of Earth system processes, Steffen et al., 2004 discovered that there were no known processes that are *not* non-linear.

23 High dams are defined as dams that are taller than 15 metres. The figure of 40,000 for the number of existing high dams worldwide is probably an underestimate, but it pays to work with conservative figures when even they correspond to massive disruptions.

(WWF, 2018). The impact of high dams needs to be put in the wider context of studies that have found that high dams have not even passed standard tests of economic costs and benefits as a general rule.

## Regime Shifts and Tipping Points

2.54 Non-linearity of ecosystems creates further complexity. They harbour more than one *stability regime*. This means that the possible states of any ecosystem can be divided into regimes, with the property that once the system enters a regime, it is confined to it, unless it experiences a large disturbance. It is common practice today to measure an ecosystem's resilience by the extent to which it can recover from disturbances unaided. The move from one stability regime into another is called a *regime shift* (illustrated in Figure 2.L).[24] It is now also common to say that regime shifts occur at *tipping points*. Disturbances that cause an ecosystem to move from one regime (e.g. a freshwater lake in an oligotrophic state with low nutrient content and rich in oxygen) to another (e.g. the same lake in a eutrophic state where it is rich in nutrients with a dense plant population and low in oxygen) need not, of course, take place all at once. They could be accumulations of small changes, until a further small change tips the system into another regime. Non-linearities in ecosystem processes also lead to segmentations among ecosystem populations. They are exemplified by spatial segmentation of ecosystems into assemblages. Box 2.E illustrates two examples of this phenomenon.

### Box 2.E: Non-linearities in ecosystem processes leading to segmentation in populations: Examples from human health

Human Metabolic Processes - The human body is an ecosystem. Someone experiencing a breakdown in health undergoes a regime shift. Non-linearities in human metabolic processes lead, most prominently in developing countries, to a separation of human populations into groups that are healthy (e.g. people who enjoy recommended body mass indices) and groups that are malnourished. The latter group are trapped in poverty, which is formally a stability regime (Dasgupta and Ray, 1986). Of course, shifts in policy (e.g. socio-economic support by government or the community) can prevent people from getting caught in a poverty trap (Dasgupta and Ray, 1987). Technically, that would amount to a policy that keeps people from entering a stability regime that entails being 'malnourished'.

Infectious Diseases Processes - Processes driving the spread of infectious diseases are also non-linear. Globalisation and our remarkable ability to enter every ecological niche that exists has raised the chances of pandemics. Humans now enter niches occupied by organisms with which we have not evolved. That exposes us to unfamiliar pathogens. 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 (Daily and Ehrlich, 1996). That too points to non-linearities. Epidemiologists have stressed these non-linearities in studies of the spread of diseases. 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

[24] See: Scheffer and Carpenter, 2003; Scheffer, 2009; Scheffer et al., 2012.

goods make the socio-ecological world brittle in many ways. The human economy has eroded what systems analysts call 'modularity' (Levin, 1999). Various parts of the global economy are connected more strongly with one another than previously, which means a shock to any one part reverberates across the entire economy.

2.55 An ecosystem in an *un*healthy state could also be resilient, meaning that it would take effort and a good deal of time to coax it back to health. That is a display of *hysteresis*, whereby the return path from state B to state A inevitably differs from the original journey from A to B. In the extreme, a regime shift can be irreversible. These technical ideas are developed carefully in the Review because they have enormous policy implications. That the processes driving ecosystems display hysteresis means that, other things equal, it is more cost-effective to maintain an ecosystem than it is to degrade and then restore it: conservation trumps restoration.

2.56 The point at which a specific change in the external driver would lead to the ecosystem tipping into a different stability regime is never known with certainty.[25] The Review reports on features of ecosystems that provide early warning signs of regime shifts. It also identifies conditions on the state of an ecosystem that decision makers could use to judge when current practices need to be reversed.

2.57 Ecosystem flips to new states have been observed to occur at many speeds and scales. Shallow lakes have been known to flip from clear to turbid water in a matter of months, village tanks in a matter of weeks, garden ponds in a matter of hours. Insect populations have been known to crash or explode in a matter of days, and undetectable viruses spread as pandemics in a matter of weeks. Larger ecosystems generally take longer to flip because the underlying processes are slow. Grasslands can take decades to change into shrublands, and rainforests into savannah (an example illustrated in Box 2.F). The Atlantic 'salt conveyor' that helps to drive global ocean circulation would probably take decades to shut down (or change direction) if the Polar ice cover were to melt at rates estimated in current models of global warming. Fossil records suggest that the interglacials and glacials of ice ages have appeared only occasionally but have arrived and departed precipitously – the flips occurring over several thousand years.

2.58 Regime shifts have already played havoc with the lives of deprived people living in rural economies. They are not to be thought of only as harbingers of economic stresses to come in future. When micro-watersheds have experienced soil erosion or when coastal fisheries have been polluted by phosphorus and nitrogen inflow and lost productivity, rural communities have suffered. The Review provides an account of economic history in deep time and reports examples from the findings of paleo-anthropologists on successes and failures of past societies to overcome environmental stresses (e.g. climate change, soil erosion).

25 A change could be the subtraction of a single species or number of species, a change in abundance, or a change in community composition.

## Box 2.F: The point of no return: A shift from rainforest to grassland

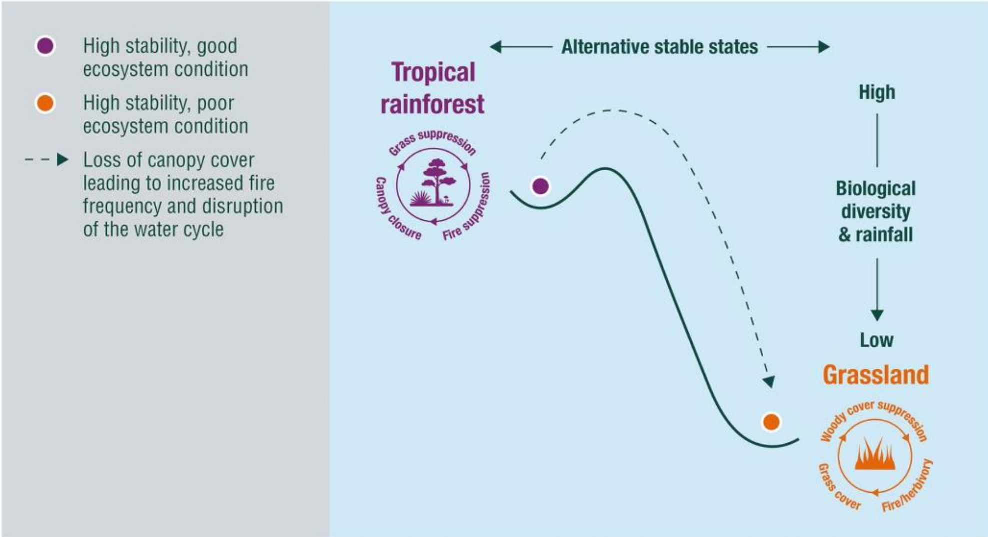
It is well established that under certain conditions, tropical rainforest can shift to grassland (savannah). This has significant consequences for the water cycle of the surrounding region: trees of a tropical forest take up large volumes of water from the ground and release it through transpiration. This governs the amount of water in the local atmosphere, maintaining high levels of rainfall. Rainfall returns water to the ground for trees to take up and transpire; when deforestation occurs, water's link between the soil and atmosphere is lost.

Forest and savannah are alternative stable states for tropical land, maintained by feedback loops of fire (in the case of savannah), and fire suppression (in the case of rainforest). When rainfall levels are low, vegetation is dominated by grasses with very limited wood cover providing shade. Therefore, the intensity of the sun can easily start fires, creating a 'trap' for any developing woody cover, and making the return shift to forest extremely unlikely. High levels of rainfall enable wood cover to grow and develop into canopies, which then maintain the necessary water cycle (as described above), and provide shade which limits the possibility of fire breaking out (Oliveras and Malhi, 2016). Increased deforestation increases the likelihood that the ecosystem will 'tip' from forest to savannah. Figure 2.L depicts these alternative stable states and the feedback loops which maintain them.

If deforestation goes beyond a certain point, rainforests will no longer be able to maintain the level of moisture they need in the atmosphere, and no longer be able to shade their forest floor from fire. This will have serious consequences for rainfall levels in their entire regions: levels of deforestation in the Southern Amazon have already caused rainfall to significantly decrease there (Debortoli et al., 2015; Chambers and Artaxo, 2017).

Before the large-scale wildfires in 2019, analysis from Lovejoy and Nobre (2018) suggested that if deforestation reached 20-25% of the Amazon's original forest area, the southern, eastern, and central regions will become savannah, with enormous consequences for the water cycle on a global scale causing major climatic disruption. Since 2018, deforestation in Brazil has spiked by around 30%: in 2019, 10,000 $km^2$ was lost (the largest loss in a decade) (Amigo, 2020). In late 2019, Lovejoy and Nobre stated that current Amazon deforestation stands at 17%, dangerously close to the 20-25% figure which could trigger a tipping point for the entire region (Lovejoy and Nobre, 2019). The total impact of the 2019 Amazon forest fires has yet to be quantified. In September 2019, a group of researchers formed the Science Panel for the Amazon, which will report on the state of the forest following the fires and suggest actions for its conservation. The consequences of such a large-scale shift in the Amazon's hydrological system will be extreme: every country in South America benefits from the Amazon's moisture (except for Chile as it is blocked from this moisture by the Andes). Human well-being will suffer: food production and water availability across the continent will be damaged. Lovejoy and Nobre (2019) argue that the tipping point is fast approaching, but that with will and imagination, urgent action can make its future sustainable.

## Figure 2.L: Tipping points




*Note: Graphic showing the concept of tipping points.*

# Why we degrade the biosphere when it undermines our wellbeing

2.59 Why are our individual actions working against our collective interest in ways that increase the difference between demand and supply in the Impact Inequality? Given human societies and economies depend on the biosphere, why are we degrading it?

## Institutional failures

2.60 The mismanagement of the biosphere reflects *institutional failure* writ large – it is not simply *market failure*.[26] An overarching pathway giving rise to institutional failure involves the externalities that our use of Nature's services give rise to. Of significance is the fact that much of Nature is free at source and open to all, limiting incentives to curb our demand. Because much of Nature is free, we do not account for the adverse consequences of our actions on others, including future generations. One reason it has proved so hard to bring individual and collective interests in line with one another is that much of Nature is always on the move: the wind blows, water flows, the oceans circulate, and birds and insects fly. That makes property rights difficult to define, let alone enforce.[27] *Property rights* refer not only to private rights, but also to community, national, and international rights. Ecosystem services should be priced in ways that reflect their relative social scarcities, but that is rarely the case. The current structure of market prices works against our biosphere, which

26 The literature on the economics of global climate change has popularized the view that excessive global emissions of carbon into the atmosphere is a case of market failure. Repeated failure of governments to implement their several accords shows why broader institutional failure is at play.

27 To say that an ecosystem is a "common property resource" is not to say that it is "open-to-access". Societies have in the past devised institutions, such as adopting norms of behaviour, which ensured that their local common property resources, such as forests, ponds, coastal fisheries, grazing land, and threshing grounds, were not subject to over-use. The Review considers the extensive anthropological literature on this.

is precious but priced cheaply. The resulting excess demands for 'common property resources' are often called the *tragedy of the commons* (Hardin, 1968).

2.61 Because the consequences of ecosystem degradation are always uncertain, the economics of biodiversity must contend with *risk externalities*. Environmental risks are positively correlated among people. When mangrove forests are replaced by shrimp farms, there is heightened risk of damage from cyclones because those mangroves previously provided coastal protection. That heightened risk is felt not by one individual alone, but also by their neighbours. Insurance markets are unable to function well with correlated risks. Their inability is greater the larger the population subject to the correlated risk. The Review studies environmental risks from the localised (where governments can help citizens by working with the private sector to provide co-insurance), to the global (where national governments on their own would not be able to provide co-insurance).[28] In contrast, some conservation and restoration measures are designed to reduce the risk of ecological degradation, while others are aimed at reducing the damage caused by ecological degradation.

2.62 Governments almost everywhere exacerbate the problem of the commons by paying people to exploit the biosphere. These payments have been called *perverse subsidies*. They reduce the price users pay for the global commons from zero to negative figures. Examples include subsidies to agriculture, water, fossil fuels and fisheries, as well as subsidies to inputs to production like energy and fertilisers. These subsidies further encourage over-extraction and harvesting of the biosphere. Government subsidies for exploiting Nature are extensive in size: a conservative estimate is between US$4-6 trillion globally per year for the sectors mentioned above (OECD, 2017; Andres et al., 2019; Coady et al., 2019). The figures dwarf the size of finance for conservation and restoration of the biosphere – domestic public finance for biodiversity-related activities was US$67.8 billion per year on average between 2015 and 2017 (OECD, 2020). Estimates of wider finance flows to biodiversity (for example, from economic instruments, philanthropy and impact investing) are between US$10.2 billion and US$23.2 billion per year (OECD, 2020).

2.63 These institutional failures affect the deployment of technology. When faced with market prices that do not reflect accounting prices, technological advances can exacerbate the problem. Understandably, entrepreneurs develop technologies that economise on the expensive inputs in production, not the cheap ones. Regulating and maintenance services are (perversely) cheap relative to produced and human capital – as we have seen, in the extreme, the former have a negative price tagged on to them – so it should not be surprising that over the past century or more many new technologies have been rapacious in their reliance on Nature.

2.64 Moreover, technological advances can have side-effects on ecosystems which, even though they may be unintended, are not benign. In shrimp trawling, other marine species are caught unintentionally and wasted (known as *bycatch*). Modern fishing technology can devastate large swathes of seabed. Technologies like bulldozers and chainsaws allow for deforestation at rates that would have been unimaginable 250 years ago. To be sure, there is potential for technology – including those associated with the "Fourth" Industrial Revolution such as artificial intelligence, satellite imagery and drones – to be forces that help to conserve and restore the biosphere (Herweijer et al., 2018), but they can only be harnessed on a

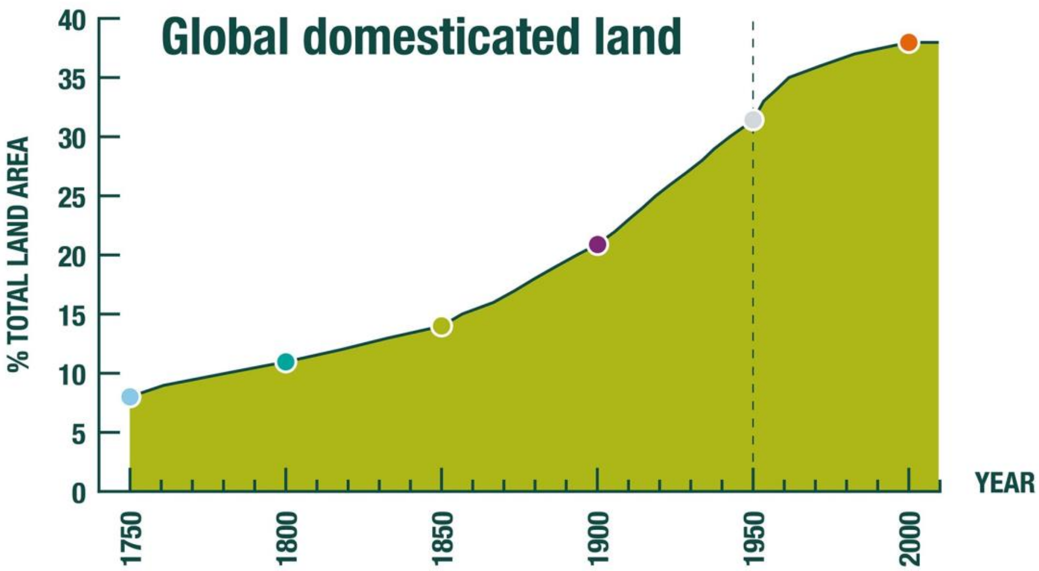
[28] There are a number of initiatives that involve insuring Nature, Kousky and Light (2019) have developed this line of inquiry.

systematic basis if the price we pay for regulating and maintenance services reflect their social scarcity values.

2.65 It was not until the middle of the last century that technologies to extract or harvest provisioning services (like food, fibre, timber and fish) and transport them across the globe were developed at a sufficiently low cost to cause the tragedy of the commons globally. By 2015, 93% of fisheries were either overfished or being used at maximum capacity sustainable levels (FAO, 2018). The externalities have escalated with growth in global population, advances in technology that have lowered harvesting and transport costs, and the consequent increase in trade. The widening of the Impact Inequality is a formal reflection of that.[29] Markets have developed over centuries to mediate our transactions in provisioning services, with growing global trade in food, fibres, and timber. But many regulating and maintenance services remain outside economic systems, which is why people do not have incentives to act in ways that account for their relative scarcity.

2.66 The clash between provisioning services and regulating-maintenance services has been accentuated with population growth (N), rising standards of living and changing consumption patterns (y). There has been an increase in global demand for provisioning goods and services like food, fibre, timber and fuel. This increase in demand is illustrated in Figure 2.M, which shows the increase in domesticated land, measured by agricultural land area, including cropland and pasture, as a percentage of total land area (Steffen, Broadgate, et al., 2015). This has come at the cost of regulating and maintenance services, and in great measure cultural services too.[30]

Figure 2.M: Global domesticated land as a proportion of total land area




Domesticated land = Agricultural land area (including cropland and pasture) as a percentage of total land area.

*Note: Graph of global domestic land percentage. Source: Steffen, W., Broadgate, W., et al. (2015) 'The trajectory of the anthropocene: The great acceleration', Anthropocene Review, 2(1), pp. 81–98.*

29 Dasgupta, Mitra, and Sorger (2019) contains a formal demonstration that open-access resources are over-exploited when population relative to harvesting costs is large, but not otherwise.

30 This has been a central message of both the Millennium Ecosystem Assessment (2005) and IPBES global assessment (2019).

2.67 In looking at institutions that can address institutional failure, the Review collates an extensive anthropological literature on rural poverty and degradation of local ecosystems. It applies economic analysis to understand the links between rural poverty in the world's poorest countries and the state of their local environmental-resource base. It studies the interplay of property rights, the practice of social norms, the operation of markets, the resilience of communities, the trustworthiness and competence of the state, and the character of ecosystems that shape the lives of the poor. Institutions vary by ecosystem: those that work well for communities living in a tropical rainforest differ from those that work well in temperate grasslands. The Review concludes, however, with a general finding, applicable to almost all ecosystems: neither top-down nor bottom-up institutional structures work well. What the inhabitant of an ecosystem knows and can observe differs from what an agent from government knows and can observe. Moreover, institutions that work well are neither entirely rigid nor entirely flexible – they are polycentric, a structure of governance that accommodates best the fact that information is asymmetrically distributed among members of any society.[31]

## Standard economic models view economies as outside the biosphere

2.68 Standard models of economic growth and development do not recognise the biosphere explicitly. They see humanity as being able to operate *externally* to Nature. In this view, people are seen as dipping into the biosphere for its goods and services, transforming them in the form of output and services for production and consumption, and returning our waste back to Nature. These models are used by economists to understand the factors that affect economic growth. They focus on technology, produced capital and human capital. In some versions of modern growth economics, exhaustible natural resources are seen to be factors of production, but the focus there has been to show that technological progress can, in principle, counter their exhaustibility. This view – that if humanity is sufficiently ingenious it can expect indefinite economic growth – is ingrained in contemporary thinking, and pervasive even in the economics of climate change.[32]

2.69 Viewing humanity and the human economy as external to Nature is also embodied by the most commonly used measure of economic success: Gross Domestic Product (GDP) – the market value of final goods and services, which is a measure of economic activity.[33] As noted earlier, the Review uses GDP as a measure of human activity in the Impact Inequality.

2.70 GDP remains essential in short-run macroeconomics as a measure of economic activity. The measure allows economists to estimate the gap between the economy's potential output and actual output and is useful also for studying household and corporate behaviour to inform macroeconomic policymaking. But GDP does not measure an economy's 'productive capacity', which is the measure proposed implicitly in the Report of the Brundtland Commission of 1987 on Environment and Development (Brundtland, 1987). That report defined sustainable

---

31 A rich literature on the economics of information pointed to polycentricity as a commendable institutional structure. However, the term itself was introduced into institutional economics by Ostrom, (2010).

32 See for example, Nordhaus (1994), Aghion and Howett (1998), Barro and Sala-i-Martin (2003), Stern (2006), Acemoglu (2008), Galor (2011), among many others.

33 Formally, it is the market value of the flow of final goods and services in a country in a given year.

development as a path of economic development whereby each generation leaves behind at least as large a stock of assets as it itself inherited. The formal notion of an economy's productive capacity is *wealth.* GDP is a *flow* (dollars per unit of time), in contrast to wealth, which is a *stock* (dollars). We do not bequeath income to our descendants (a flow's variables cannot be handed over); what we bequeath to them are forms of wealth, which give them access to a flow of income. Moreover, GDP ignores the depreciation of capital goods. It could be that a country produces goods and services by running down its assets, in which case GDP could grow for a period, while capital goods, including natural capital, depreciate. Assessing an economy on the basis of GDP alone is like examining a company's income statements without considering the assets on its balance sheet. The company's income may look good for a short time, but liquidating assets over the long run reduces productive capacity for generating income in the future.

2.71 Arguably, the view of the economy as external to the environment may have been comparatively harmless so long as the biosphere was more than able to supply the demands humanity made of it. That simply is not the case any longer and has not been for many decades.

2.72 The Review, in contrast, views the global economy as *embedded* in Nature. As the Impact Equality shows, this has far reaching and profound implications. Growth in global output (Ny) can grow indefinitely only if the efficiency with which we are able to transform the biosphere's goods and services into final products (i.e. $\alpha$) also grows indefinitely. As was noted above, for perpetual economic growth to be possible, we must therefore imagine that the additional demand we would make of the biosphere for investment in science and technology will be vanishingly small no matter how large income per capita happens to be in the future. That is the sense in which contemporary growth and development economics and, by extension, the economics of climate change views the human economy as external to the biosphere.

## Ends and means: The equivalence between well-being across generations and inclusive wealth

2.73 The Impact Inequality is meaningful only for the global economy. Agents, or actors, in smaller economic units, such as national economies down to the level of households, need to know whether the decisions they take are likely to sustain, or even raise, the well-being of those in their 'unit' and the well-being of those that come after them. That is the role of sustainability assessment. All such agents need a criterion with which they can compare alternative decisions, when the end they seek is their well-being and the well-being of future generations. The criterion can then serve policy analysis.

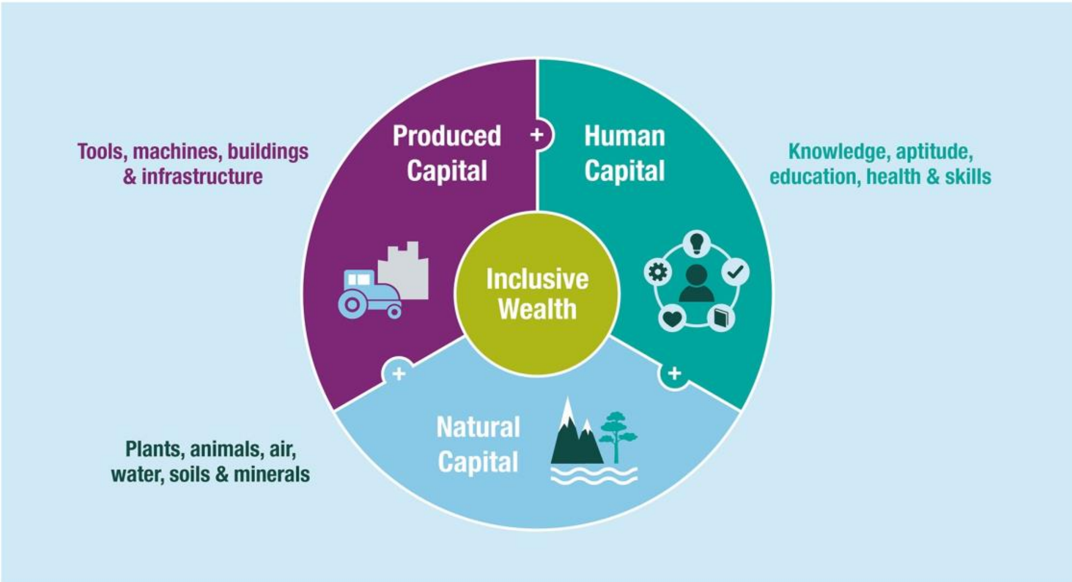
2.74 A specific example is national economies. The person engaged in economic evaluation could be a citizen, civil servant, member of a national parliament, and so on. In the Review we name her the *social evaluator*. We may imagine her to be the decision-maker too. She decides on behalf of her society and so evaluates alternative economic paths on the basis of a conception of well-being, not only of present people but also the potential well-being of future people.[34] An example is the Utilitarian conception of intergenerational well-being that has shaped the

[34] This is of course only a thought exercise. It is designed to capture the idea that a government serves the common good.

economics of climate change (e.g. Cline, 1992; Nordhaus, 1994; Stern, 2006). The Review also explores non-Utilitarian conceptions, including a number of indigenous conceptions of what is 'good', many of which place a value of Nature that is non-anthropocentric. To keep in line with terminology in the economics of climate change, we call the social evaluator's objective 'social well-being'.

2.75 The accounting price of a capital good is the contribution a marginal unit would make to social well-being. It follows that the worth of the economy's stock of a capital good is its accounting price multiplied by its quantity. We call that the stock's 'accounting value'. In turn, we call the accounting value of an economy's total capital goods – produced, human, and natural capital – its *inclusive wealth*, illustrated in Figure 2.N.[35] The qualifier signals that the notion of wealth adopted here differs from the one in common use in two ways: (i) accounting prices are not necessarily market prices; and (ii) in addition to produced capital, wealth includes human capital and natural capital.

Figure 2.N: Inclusive wealth




*Note: Graphic illustrating inclusive wealth.*

2.76 What about institutions? They too are assets. The Review does not include them in the three-way classification of capital goods but instead sees them as endowing the capital goods with their social worth. Institutions and practices are referred to in the Review by the term *enabling assets*. It follows that a society does not have to rely on accumulating capital goods in order to increase inclusive wealth; it could raise inclusive wealth simply by bringing about such changes to its institutions and practices that create greater trust among people (sometimes referred to as *social capital*). The changes would express themselves through an altered set of accounting prices for the same portfolio of capital goods. A writing desk has a higher accounting price (as a desk) in someone's study than in a war zone. An economy can become wealthier simply by improving the quality of its enabling assets.

35 Reference to inclusive wealth was made previously, in Fig. 2.G.

2.77 Why should we be interested in inclusive wealth? The reason lies in **The Wealth/Well-Being Equivalence Theorem:** any small change experienced by an economy which leads to an increase (decrease) in social well-being also leads to an increase (decrease) in inclusive wealth.[36]

2.78 Inclusive wealth and social well-being are *not* the same entity, but they move in step with each other: there is perfect correspondence between the two. Inclusive wealth and social well-being are two sides of the same coin; to maximise inclusive wealth is to maximise social well-being.

2.79 We are talking of ends and means here. The wealth/well-being equivalence theorem does not deny the antecedence of ends; what the theorem says is that if the means to a set of ends have been identified, it does not in principle make any difference whether we examine the extent to which the ends have been (or are likely to be) furthered by a change to an economy, or whether we estimate the degree to which the means to those ends have been (or are likely to be) bolstered by that change: the two point in the same direction. The wealth/well-being equivalence theorem draws attention to the fact that no matter what conception of ends citizens may adopt, the source of the means to those ends lies in a society's capital goods. Their accounting prices serve to tie them to the ends. The theorem says, for example, that steel put to use in making ploughs has an accounting price that differs from steel used to manufacture guns. Accounting prices of capital goods depend on their location and the use to which they are put.

2.80 The equivalence between inclusive wealth and social well-being holds as tightly in a society where the ends are far from being met owing to misallocation of the means or unjustified usurpation of the means by the powerful, as it would in a society where they are met as far as is possible under the prevailing scarcities of the means. The equivalence theorem is utterly wide in its reach.

2.81 That inclusive wealth is equivalent to social well-being is not an empirical law, it is an analytical proposition. Being an equivalence relationship, it does not say whether a society is doing well or badly, whether it is well governed or badly governed. But both theory and experience say that it is commonly easier to measure the means to the ends than it is to measure the ends themselves.[37] This is why we are drawn to measure inclusive wealth (the means), rather than wellbeing (the ends).

2.82 Sustainable development requires that inclusive wealth should increase over time. That is not economic growth in the sense in which the term is universally used today, namely, growth in GDP. The central weakness of GDP is that it does not include the depreciation of capital. To overcome that weakness, it is possible to estimate *net domestic product* (NDP) which is GDP minus the depreciation of

---

36 The theorem in increasing generality was stated and proved in Dasgupta and Maler (2000) and Arrow, Dasgupta and Mäler (2003a,b). The theorem was placed in the general context of intergenerational welfare economics by Dasgupta (2004). Arrow et al. (2012) estimated movements in the inclusive wealth of a selected number of countries for the period 1995-2000. UNU/IHDP-UNEP (2012, 2014), and Managi and Kumar (2018) estimated movements in the inclusive wealth of 120 countries over the period 1995-2005. The work of various groups creating natural capital accounts, such as the UK's Natural Capital Committee and the UN System of Environmental-Economic Accounts, and advances in modelling natural capital and ecosystem services (Kareiva et al., 2011) will be the natural feeder into future, more accurate estimation of the inclusive wealth of nations.

37 An influential literature on social cost-benefit analysis (e.g., Little and Mirrlees, 1974) demonstrated why that is so.

produced capital, human capital, and natural capital in a given year. NDP can be used to translate the wealth/well-being equivalence theorem in terms of an economy's flow of output. To see how, notice that the change in inclusive wealth in a year would be NDP minus aggregate consumption. The Review calls that *inclusive investment* (Dasgupta, 2004).[38] Inclusive investment is the change in inclusive wealth in that year. The criterion for sustainable development then can be read as the condition that inclusive investment should not be negative, or in other words that aggregate consumption should not exceed NDP.

2.83 The Review shows that, when applied to policy analysis, in particular evaluation of investment projects like restoration projects, the change in inclusive wealth that is brought about by a project is none other than the *Present Discounted Value* (PDV) of the flow of net social benefits it confers on society. Evaluating a project in terms of its PDV is essentially the same as estimating its internal rate of return and accepting the project only if the return exceeds the rate at which the social evaluator discounts future benefits. That observation brings the Review back full circle to where it began. Maximising the value of an economy's portfolio of capital goods, that is, its inclusive wealth, amounts to maximising social well-being. That is the reason national economies need to create inclusive wealth accounts, and why the progress or regress of national economies should be judged on the basis of movements in their inclusive wealth, not movements in GDP.

### Developing an appreciation of Nature

2.84 All this though will not be enough. The conception of Nature and our relationship with Nature has evolved over the centuries, perhaps as recently as decades, in step with the place of Nature in economic reasoning. Many view Nature almost entirely through an anthropocentric lens, even while our affection for Nature, and even our emotional attachment to it, declines. With growing urbanisation, that process of detachment can be expected to continue, perhaps even amplify. The Review concludes with a plea for a transformation of our education systems towards one where children from an early age are encouraged to try and understand the infinitely beautiful tapestry of processes and forms that is Nature. It is only when we appreciate that we are part of Nature and that Nature nurtures us that we will have fewer needs for reviews on the economics of biodiversity.

## Identifying options for the change we need

2.85 This interim report sets out the economic and scientific concepts that will underpin the final Review. The interim report stops short of presenting options for change. These will be set out in the final Review, based on the evidence and foundational ideas set out here. The Review will identify what needs to change to make humanity's engagement with Nature sustainable. Closing the gap between our total demands on the biosphere and its ability to supply services requires a fundamental reconsideration about the sustainability of our engagements with Nature. This raises difficult questions.

2.86 Those questions include: how can we conserve and restore our natural assets; how can we consume, and manage our waste, more efficiently; is it feasible to address the imbalance between our demands and what the planet can provide, while at the same time accommodating the legitimate needs of an expanding global

---

[38] Hamilton and Clemens (1999) called it 'genuine saving.'

population; what role can technology play in addressing these challenges; what role can family planning and reproductive health play; and are our institutions fit for purpose? And in our response to each of these questions, we must ask: are we acting to the benefit of our descendants' lives? And what is the fair and just role for countries at different stages of development, given their relative contribution to the degradation of the biosphere?

2.87 In identifying options for change, the Review will:

- use the Impact Equality as the condition for global sustainability to identify what needs to change for humanity's engagement with the biosphere to be sustainable. The Review will consider all elements of the Impact Equality, on both the demand and supply side.

- consider what institutional structures are effective in making our engagement with the biosphere sustainable. Nature is different across diverse ecosystems and biomes, so different institutions emerge and succeed in different contexts. The Review will look at examples of institutions around the world, at different scales and locations, that are successfully restoring and conserving ecosystems. It will explore how societies have devised and built such institutions, drawing out insights about what makes them successful.

- set out how economic models, evaluation processes and metrics can recognise that our economies are embedded in the biosphere. The Review will set out the principles required of good economic systems and the appropriate measure of economic progress and sustainable development, based on inclusive wealth.

- identify nature-based solutions as an essential part of the package of measures to mitigate and adapt to climate change. The Review will look at how actions to mitigate and adapt to climate change can deliver benefits for biodiversity and, conversely, how conservation actions can help to address climate change.

- identify actions needed across all spheres, including communities, governments, businesses, financial institutions and the public. The Review will set out the hard choices we must all make, and the significant, coordinated actions required. The Review will revisit expectations of the costs of these transformative changes, based on an understanding of how people's preferences are affected by the choices of others (see Box 2.D).

- recognise that citizens have the power to insist that international organisations, governments, businesses and regional authorities act. The Review will therefore also explore how a sustainable future relies upon individuals caring about, and understanding, Nature, and how we impact and depend upon it.

# Chapter 3

# Next Steps

3.1 For the remainder of the Review, we will focus on:

- testing the Review's key economic and scientific concepts, summarised in this interim report;
- exploring, analysing and testing potential options for change that can both enhance biodiversity and deliver economic prosperity; and
- continuing to promote and raise awareness around the issues addressed by the Review.

3.2 We will also continue engagement with a wide range of people and organisations, including policymakers, businesses, NGOs, research organisations and others, both in the UK and internationally. In these challenging times, much – perhaps all – of our engagement will need to be done virtually, and we thank people in advance for their contributions.

3.3 We will submit a final report to the Prime Minister, Chancellor of the Exchequer and Secretary of State for the Environment, Food and Rural Affairs ahead of COP15.

## Request for feedback

3.4 To support the ongoing work of the Review, we would welcome feedback in response to the below questions relating to the detail set out in this interim report. We encourage responses that are brief and to the point. The Review team may follow up for more detail where appropriate. Please send responses to any, or all, of the questions below **by 1 June 2020** to: biodiversityreview@hmtreasury.gov.uk.

3.5 The Review team will not publish the responses in full or in summary form. However, as explained in the notice after the questions, we may be required to disclose this information under the Freedom of Information Act 2000.

3.6 Please note the important information following the questions below, which sets out how your response will be treated and how any personal data you provide which identifies you or third parties will be handled.

### Questions

1 Are there aspects of the key concepts outlined in this interim report that are not logical, clearly explained or that you have questions about? Please explain.

2 Are there any important issues or concepts not adequately considered? Please explain.

3 Are there any further suggestions you have for improving the Review's intellectual foundations on the economics of biodiversity?

4 What else should the Review consider in developing the options for change?

# Processing of personal data

## Processing of personal data

3.7 This notice sets out how HM Treasury (the data controller) will use your personal data for the purposes of this consultation for the Dasgupta Review on the Economics of Biodiversity, and explains your rights under the General Data Protection Regulation (GDPR) and the Data Protection Act 2018 (DPA).

## The data we collect about you (Data Categories)

3.8 The personal data that we collect may include the name, address, email address, job title, and employer of the correspondent, as well as their opinions. It is possible that respondents will volunteer additional identifying information about themselves or third parties.

## Legal basis of processing

3.9 The processing is necessary for the performance of a task carried out in the public interest. The task is requesting evidence or obtaining opinion data in order to develop good effective proposals and recommendations to government.

3.10 HM Treasury may use the contact details provided to contact respondents during the consultation period in order to request clarification or further information regarding the response provided where this is deemed necessary.

## Special category data

3.11 We do not expect that any special category data will be processed.

## Purpose

3.12 Any personal information will be processed for the purpose of obtaining evidence from members of the public and representatives of organisations and companies about departmental policies, proposals, or generally to obtain public opinion data on an issue of public interest.

3.13 Information and data provided to the controller in response to this call for evidence will be used by Professor Partha Dasgupta and the Dasgupta Review Secretariat to support their independent review of the economics of biodiversity.

## Whom we share your responses with (Recipients)

3.14 Information provided in response to consultations may be published or disclosed in accordance with the access to information regimes, in particular those under the Freedom of Information Act 2000 (FOIA), the Environmental Information Regulations (EIR) 2004, the GDPR and DPA.

3.15 Where you consider that the information you provide should not be disclosed under these regimes, you should state that you are providing the information in confidence and explain why you consider the information to be confidential. If the controller receives a request for disclosure of the information, they will take full account of your explanation, but they cannot give an assurance that confidentiality can be maintained in all circumstances. An automatic confidentiality disclaimer generated by your IT system will not, of itself, be regarded as binding on HM Treasury.

3.16 The Dasgupta Review's work will be independent of government. It will make a final report with its recommendations before the meeting of the Conference of the Parties to the Convention on Biological Diversity.

3.17 Where someone submits special category personal data or personal data about third parties, we will endeavour to delete that data before publication takes place.

3.18 Where information about respondents is not published, it may be shared with officials within public bodies involved in this consultation process to assist them in developing the policies to which it relates. Examples of these public bodies appear on gov.uk.

3.19 As the personal information is stored on HM Treasury's IT infrastructure, it will be accessible to HM Treasury's IT contractor, NTT. NTT will only process this data for HM Treasury's purposes and pursuant to the contractual obligations they have with HM Treasury.

## How long we will hold your data (Retention)

3.20 Personal information in responses to consultations will generally be published and therefore retained indefinitely as a historic record under the Public Records Act 1958.

3.21 Personal information in responses that is not published will be retained for three calendar years after the consultation has concluded.

## Your rights

3.22 You have the right to request information about how your personal data are processed and to request a copy of that personal data.

3.23 You have the right to request that any inaccuracies in your personal data are rectified without delay.

3.24 You have the right to request that your personal data are erased if there is no longer a justification for them to be processed.

3.25 You have the right, in certain circumstances (for example, where accuracy is contested), to request that the processing of your personal data is restricted.

3.26 You have the right to object to the processing of your personal data where it is processed for direct marketing purposes.

3.27 You have the right to data portability, which allows your data to be copied or transferred from one IT environment to another.

3.28 How to submit a Data Subject Access Request (DSAR)

3.29 To request access to personal data that the controller holds about you, contact:

HM Treasury Data Protection Unit
G11 Orange
1 Horse Guards Road
London SW1A 2HQ
dsar@hmtreasury.gov.uk

3.30 HM Treasury provides a secretariat function to the Dasgupta Review.

## Complaints

3.31 If you have any concerns about the use of your personal data, please contact HM Treasury via this mailbox: privacy@hmtreasury.gov.uk.

3.32 If HM Treasury is unable to address your concerns to your satisfaction, you can make a complaint to the Information Commissioner, the UK's independent regulator for data protection. The Information Commissioner can be contacted at:

Information Commissioner's Office
Wycliffe House
Water Lane
Wilmslow
Cheshire
SK9 5AF
0303 123 1113
casework@ico.org.uk

3.33 Any complaint to the Information Commissioner is without prejudice to your right to seek redress through the courts.

## Contact details

3.34 The controller for any personal data collected as part of this consultation is HM Treasury, whose contact details are:

HM Treasury
I Horse Guards Road
London
SW1A 2HQ
020 7270 5000
public.enquiries@hmtreasury.gov.uk

3.35 The contact details for HM Treasury's Data Protection Officer (DPO) are:

The Data Protection Officer
Corporate Governance and Risk Assurance Team
Area 2/15
1 Horse Guards Road
London
SW1A 2HQ
privacy@hmtreasury.gov.uk

# Annex A
# Acronyms

| | |
|---|---|
| CBD | Convention on Biological Diversity |
| CICES | Common International Classification of Ecosystem Services |
| COP15 | 15th meeting of the Conference of the Parties to the Convention on Biological Diversity |
| FAO | Food and Agriculture Organization of the United Nations |
| GDP | Gross Domestic Product |
| IHDP | International Human Dimensions Programme |
| IPBES | The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services |
| MA | Millennium Ecosystem Assessment |
| NDP | Net Domestic Product |
| NGO | Non-Governmental Organisation |
| NPP | Net Primary Productivity |
| OECD | Organisation for Economic Co-operation and Development |
| PDV | Present Discounted Value |
| TEEB | The Economics of Ecosystems and Biodiversity initiative |
| UNDP | United Nations Development Programme |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UN SDGs | United Nations Sustainable Development Goals |

# Annex B

# Glossary

*Accounting price:* Also called 'shadow price'. The contribution that an additional unit of a good, service or asset makes to human wellbeing across the generations, other things equal. In simple terms, accounting prices reflect the true value to society of any good, service or asset.

*Aichi (Biodiversity) Targets:* The 20 targets set by the Conference of the Parties to the Convention for Biological Diversity (CBD) at its tenth meeting, under the Strategic Plan for Biodiversity 2011-2020.

*Anthropocene:* The new geological age Planet Earth has entered in which human activity has become the dominant influence on our climate and environment (Steffen et al., 2011).

*Assemblage (in ecology):* A group of organisms belonging to a number of different species that co-occur in the same area and interact.

*Asset:* A durable object, which produces a flow of goods and/or services over time.

*Asset management:* The process of deciding which assets to hold in an asset portfolio. Asset managers make decisions based on the returns their portfolios offer with respect to what they desire to achieve.

*Biodiversity:* The variety of life in all its forms, and at all levels including genes, species, and ecosystems. The CBD defines biodiversity as 'the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems'.

*Biodiversity loss:* The reduction of any aspect of biological diversity (i.e. diversity at the genetic, species and ecosystem levels) in a particular area, which can be lost through death (including extinction), destruction or manual removal.

*Biomass:* The mass of non-fossilized and biodegradable organic material originating from plants, animals and micro-organisms in a given area or volume.

*Biome:* Biomes are combinations of ecosystems that have evolved in response to a similar physical climate, such as average rainfall and temperature patterns. Biomes include, for example, tundra, grasslands or tropical rainforests.

*Biosphere:* The combination of all the ecosystems in the world, the living organisms within them and the spaces they occupy, including on part of the Earth's crust (the lithosphere), in the oceans (the hydrosphere) and in the atmosphere.

*Bycatch:* Species caught unintentionally during a fishing process.

*Capital goods:* These include *produced capital* that are material (tangible) and alienable (i.e. whose ownership is transferable) and used in the production process to produce a finished good. Examples of *produced capital* include roads, buildings, machines, and ports. Capital goods also include intangible assets like health and education (*human capital*) and non-alienable assets like clean air (*natural capital*).

*Carrying capacity:* In ecology, the carrying capacity of a species in an environment is the maximum population size of the species that the environment can sustain indefinitely.

*Climate change:* As defined in Article 1 of the United Nations Framework Convention on Climate Change, "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods".

*Community composition:* The array of species in a specific community or area.

*Conservation:* The protection and management of biodiversity to maintain it at a threshold level.

*Cultural services:* The category of ecosystem services that includes non-material benefits that people obtain from ecosystems through recreation, tourism, intellectual development, spiritual enrichment, reflection and creative and aesthetic experiences.

*Dead zones:* Hypoxic areas in the world's oceans and large lakes caused by excessive nutrient pollution from human activities coupled with other factors that deplete the oxygen required to support most marine life.

*Degraded ecosystems (including the biosphere):* A state of an ecosystem that results from persistent decline or loss of biodiversity and ecosystem functions and services.

*Depreciation:* The decline in the value of an asset over time. In the case of natural capital, depreciation is the difference between the rate at which it is extracted and its regenerative rate. Depreciation caused by pollutants is the difference between the rate at which pollutants are discharged into the biosphere and the rate at which ecosystems can neutralise the pollutants.

*Ecological footprint:* A measure of the amount of biologically productive land and water required to support the demands of a population or productive activity. Ecological footprints can be calculated at any scale: for an activity, a person, a community, a city, a region, a nation or humanity as a whole.

*Economic evaluation:* The process of assessing whether national economies achieve ‘progress’ over time or assessing whether an investment, policy or plan will contribute to ‘progress’.

*Economic model: A* theoretical construct representing economic processes by a set of variables and a set of logical and/or quantitative relationships.

*Ecosystem:* A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.

*Ecosystem degradation:* A long-term reduction in an ecosystem’s structure, functionality, or capacity to provide benefits to people.

*Ecosystem / ecological engineering:* Approaches that use ecology and engineering to design, construct or restore, and manage ecosystems that integrate human society with Nature, for the benefit of both. (Mitsch and Jorgensen, 1989)

*Ecosystem function:* The flow of energy and materials through the biotic and abiotic components of an ecosystem. It includes many processes such as biomass production, trophic transfer through plants and animals, nutrient cycling, water dynamics and heat transfer.

*Ecosystem productivity:* Ecosystem productivity refers to the rate of generation of biomass in an ecosystem. It is usually expressed in units of mass per unit surface (or volume) per unit time.

*Ecosystem services:* The benefits people obtain from ecosystems. CICES divides them into supporting services and final services (regulating and maintenance, provisioning and cultural). In the Millennium Ecosystem Assessment, ecosystem services are divided into supporting, regulating, provisioning and cultural.

*Efficient portfolio:* This occurs when assets in a portfolio yield the same rate of return, as estimated by the manager, corrected for risk.

*Enabling assets:* Assets that are not included in the three-way classification of capital goods for Inclusive Wealth (human capital, natural capital and produced capital), but endow these capital goods with their social worth. These include institutions and practices that create greater trust among people (sometimes referred to as *social capital*).

*Externality:* A positive or negative consequence (benefits or costs) of an action that affects someone other than the agent undertaking that action and for which the agent is neither compensated nor penalised through the markets.

*Extinction:* The dying out or extermination of a species. Extinctions can be global or at smaller scales i.e. local extinctions. Extinction rates refer to the number of species that go extinct during a unit of time.

*Factors of production:* The inputs needed for the creation of a good or service.

*Functional diversity:* The range of species and organism traits that influence the functioning of an ecosystem.

*Geo-engineering:* Deliberate large-scale intervention in the Earth's natural systems to counteract climate change, such as green-house gas removal.

*Global ecological footprint:* The *Global Footprint Network* indicator defines the global ecological footprint as the surface area of biologically productive land and sea needed to supply the resources we consume (food, fibres, wood, water) and assimilate the waste we produce (materials, gases). The Dasgupta Review's formal modelled expression of the global ecological footprint is the world population's demands on the biosphere per unit of time.

*Good quality of life:* The achievement of a fulfilled human life is a notion which varies strongly across different societies and groups within societies. It is a context-dependent state of individuals and human groups, comprising aspects such as access to food, water, energy and livelihood security, and also health, good social relationships and equity, security, cultural identity, and freedom of choice and action (IPBES, 2019).

*Gross Domestic Product (GDP):* The market value of the final goods and services an economy produces during a specific time period (a *flow).*

*Holocene:* The current geological age, which began approximately 11,000 years ago after the last glacial period. Some argue that we have now moved to a new geological era, known as the 'Anthropocene', characterised by extensive human activity.

*Hysteresis:* The dependence of the state of a system on its history or historical path to that state.

*Impact Equality:* A condition for sustainability of the biosphere over the long run, which conceptualises our demands on the biosphere and its supply of services.

*Impact Inequality:* Serves as a rule of thumb for explaining humanity's overshoot in its demands on the biosphere and how to address it.

*Inclusive investment:* The change in inclusive wealth in a year, which is Net Domestic Product minus aggregate consumption (Dasgupta, 2004). Hamilton and Clemens (1999) called it 'genuine saving'.

*Inclusive wealth:* The social value of an economy's total stock of natural, produced and human capital or assets.

*Indicators:* A quantitative or qualitative factor or variable that provides a simple, measurable and quantifiable characteristic or attribute responding in a known and communicable way to a changing environmental condition, to a changing ecological process or function, or to a changing element of biodiversity.

*Institutional failure:* These include (i) law and policy failures (e.g. perverse subsidies), (ii) market failures (externalities in the use of public goods and services), (iii) organisational failure (e.g. lack of transparency and political legitimacy in decision making) and (iv) informal institutional failures (e.g. breakdown of social norms due to erosion of trust.

*Institution:* An established law, custom, usage, practice, organisation, or other element in the political or social life of a people. More broadly, institutions are the *arrangements* that govern collective undertakings, including legal entities like the modern firm, communitarian associations, markets, rural networks, households and governments.

*Land use:* The human use of a specific area for a certain purpose (such as residential; agriculture; recreation; industrial, etc.). Land use change refers to a change in the use or management of land by humans.

*Market price:* The price at which a good, service or asset is exchanged for in a market.

*Millennium Ecosystem Assessment:* The Millennium Ecosystem Assessment is a major assessment of the human impact on the environment published in 2005.

*Mitigation:* An intervention to reduce negative or unsustainable uses of biodiversity and ecosystems.

*Natural assets:* Naturally occurring living and non-living entities of the Earth, together comprising the bio-physical environment, that jointly deliver ecosystem services to the benefit of current and future generations.

*Natural capital:* Natural capital is a term used to describe the stock of renewable and non-renewable natural resources (e.g. plants, animals, air, water, soils, minerals) that combine to yield a flow of benefits to people, both directly (e.g. by delivering clean air) and indirectly (e.g. by underpinning the economy). The term 'natural capital' is used to emphasise it is a capital asset, like produced capital (roads and buildings) and human capital (knowledge and skills).

*Nature:* Nature refers to the natural world with an emphasis on its living components.

*Nature's contributions to people (NCP):* All the contributions, both positive and negative, of living nature (i.e. diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to the quality of life for people. Beneficial contributions from Nature include such things as food provision, water purification, flood control, and artistic inspiration, whereas detrimental contributions include disease transmission and predation that damages people or their assets. (IPBES, 2019)

*Net Primary Productivity (NPP):* The total amount of solar energy that is fixed by photosynthesis, less the amount of energy lost to the environment as respiration (which is the energy that is available to others to consume).

*Non-linearity:* In a nonlinear relationship, the output does not change in direct proportion to a change in any of the inputs. There is not a straight-line relationship between an independent variable and a dependent variable.

*Own rates of return:* An asset's own rate of return is its marginal yield per unit of time (marginal product).

*Perverse subsidies:* Government payments to activities that exploit the biosphere, thereby reducing the price users pay for the global commons from zero to negative figures.

*Planetary boundaries:* Earth system processes critical for maintaining the stable state of the Holocene, such as biosphere integrity, land use change and climate change. Although not all these processes have definable single thresholds, crossing the boundaries increases the risk of large-scale, potentially irreversible, environmental changes.

*Polycentric governance:* A governance system in which multiple governing bodies interact to make and enforce rules within a specific policy arena or location. It is considered to be one of the best ways to achieve collective action in the face of disturbance change. (Stockholm Resilience Centre, Biggs et al., 2012)

*Portfolio:* A grouping of assets. Assets in an efficient portfolio yield the same rate of return, as estimated by the manager, corrected for risk.

*Protected area:* A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of Nature with associated ecosystem services and cultural values.

*Provisioning services:* The vast range of products we obtain from ecosystems e.g. food, freshwater, fuel, fibre, medicines, genetic resources and ornamental resources.

*Rate of return:* The rate of return on an asset is its yield plus the capital gains it enjoys over a unit of time.

*Regenerative rate (of an ecosystem):* The rate at which an ecosystem forms new organic matter per unit of item. The regenerative rate of an ecosystem can be measured using the proxy of NPP.

*Regime shift(s):* Substantial reorganisation in system structure, functions and feedbacks that often occurs abruptly and persists over time, and which moves a system from one state into another.

*Regulating and maintenance services:* All ways in which ecosystems control or modify biotic or abiotic parameters that define the environment of people. These are ecosystem outputs that are not consumed but affect the performance of people and their activities. (CICES, 2018)

*Resilience:* The magnitude of disturbance that an ecosystem or society can undergo without crossing a threshold to a situation with different structure or outputs i.e. a different state. Resilience depends on factors such as ecological dynamics as well as the organisational and institutional capacity to understand, manage, and respond to these dynamics.

*Restoration:* Any intentional activities that initiate or accelerate the recovery of an ecosystem from a degraded state.

*Risk:* This is the probability that an outcome (or investment's actual gains) will differ from an expected outcome (or return).

*Social capital:* Networks, shared norms, values and understandings that facilitate co-operation within, or among, groups. These are intangible but quantifiable factors that affect the productivity of capital goods, for example, government effectiveness and the rule of law.

*Social wellbeing:* A measure of the extent to which a society's informed desires are realised.

*Socially embedded preferences:* Human preferences which are significantly influenced by the choices of others. This can include the desire to compete or conform with others.

*Species:* An interbreeding group of organisms that is reproductively isolated from all other organisms, although there are many partial exceptions to this rule.

*Stability regime:* Stable state, in terms of a set of unique biotic and abiotic conditions, that an ecosystem can exist. Ecosystems can exist under multiple alternative stability regimes. These alternative states are considered stable over ecologically relevant timescales. Ecosystems may transition from one stability regime to another, in what is known as a *regime shift* when perturbed.

*Supporting services:* This category includes ecosystem services that are necessary to produce provisioning, regulating, and cultural services. They include soil formation and retention, nutrient cycling, water cycling, oxygen production through photosynthesis, and primary production. Broadly speaking, supporting services differ in that their influences on human life are either indirect or occur over the long run.

*Sustainable:* A situation is *sustainable* if it can persist indefinitely. An *unsustainable* state of affairs cannot persist indefinitely.

*Sustainability:* A characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs.

*Sustainable Development Goals (SDGs):* A set of goals adopted by the United Nations in 2015 to end poverty, protect the planet, and ensure prosperity for all, as part of the 2030 Agenda for Sustainable Development.

*Sustainable use (of biodiversity and its components):* The use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations.

*Tipping point:* A set of conditions of an ecological or social system where further perturbation will cause rapid change to a new state and prevent the system from returning to its former state.

*Trade-off:* A trade-off is a situation where an improvement in the status of one aspect of the environment or of human well-being is necessarily associated with a decline in or loss of a different aspect.

*Uncertainty:* Any situation in which the current state of knowledge is such that: the order or nature of things is unknown; the consequences, extent, or magnitude of circumstances, conditions, or events is unpredictable; and, credible probabilities to possible outcomes cannot be assigned. Uncertainty can result from lack of information or from disagreement about what is known or even knowable.

*Valuation:* The process of collecting and synthesising estimates the worth of a natural asset to particular people or society i.e. its ‘accounting price’.

*Well-being:* A measure of the extent to which a person’s informed desires are realised.

*Zoonotic diseases:* Zoonotic diseases (or infections) are naturally transmitted between vertebrate animals and humans.

*Zoonotic pathogen:* A bacterium, virus or other microorganism that can cause zoonotic disease.

# Annex C

# Formal treatment of the Impact Inequality

C.1 The world population's demands on the biosphere per unit of time is called the *global ecological footprint*. To construct a quantitative expression of the footprint, we 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 people 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 the Review). Let $N_i$ by the population size of $i$ and $y_i$ an index of human activity per person in $i$ per unit of time. Then $N_iy_i$ is aggregate activity by members of $i$.

C.2 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 $i$; 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 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 under-estimate of the activity of the average person in $i$, we shall use it as a proxy.

C.3 As we are studying the global economy, let $N$ denote the global population, $y$ per capita global GDP, and let $i$ cover the world's population. Then

$$Ny = {}_i\Sigma N_iy_i \qquad (1)$$

C.4 We now trace $y$ to the biosphere's goods and services.

C.5 The demands we make of the biosphere take two forms: (i) We draw upon Nature's goods and services for consumption and production; (ii) we use the biosphere as a sink for our waste products. Goods such as fish, fibre, and fresh water, and services such as pollination, water purification, and flood protection are examples of (i); while landfills, rivers carrying pollutants into estuaries, and carbon concentration in the atmosphere are examples (ii). 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.

C.6 Let $\alpha_X$ be a numerical measure of the efficiency with which the biosphere's goods and services are converted into GDP; and let $\alpha_Z$ be a numerical measure of the extent to which the biosphere is transformed by our waste products (the latter in part depends on the extent to which we treat our wastes before discharging them). So we have $X = Ny/\alpha_X$ and $Z = Ny/\alpha_Z$. The proxy measure of the global ecological footprint is thus $Ny/\alpha_X + Ny/\alpha_Z$. The distribution of global GDP affects the efficiency coefficients $\alpha_X$ and $\alpha_Z$, but here we are concerned with global aggregates.

C.7 We now turn to the biosphere's ability to provide goods and services. Let $G$ denote the biosphere's regenerative rate (NPP). $G$ is a function of the biosphere as a stock, 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 the biomass in every square on the grid, measure the biomass in it and estimate the weighted sum of biomass across the entire grid. That would be $S$. The weights to use are known as accounting prices. As of now we have only the patchiest idea of how to estimate them for constructing $S$. 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.

C.8 G is a declining function of $S$ at large values of $S$. The analogy is with fisheries, which is bounded in extent and so has a finite carrying capacity. *That means the global economy is bounded by the biosphere as a constraining factor, a fact absent from standard models of economic growth and development* (Barro and Sala-i-Martin, 2003; Acemoglu, 2008). However, in the range of stocks we are concerned with here (stocks below the level capable of sustaining maximum sustainable yield), $dG/dS > 0$.[1]

C.9 Over some decades aggregate demand per unit of time, $Ny/\alpha_X+Ny/\alpha_Z$, has exceeded aggregate supply $G(S)$ per unit of time:

$$Ny/\alpha_X+Ny/\alpha_Z > G(S) \qquad (2)$$

C.10 That has meant $S$ has declined; thereby $G(S)$ has declined.

[1] 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. The Review will show how policy can be designed in a stochastic world.

# Annex D

# References


Acemoglu, D. (2008). *Introduction to Modern Economic Growth*. Princeton University Press, Princeton, New Jersey.

Aghion, P., & Howitt, P. (1998). *Endogenous Growth Theory.* MIT Press, Cambridge, MA.

Amigo, I. (2020). 'The Amazon's Fragile Future', *Nature*, 578: 505–7.

Anderson, R., & May, R. M. (1991). *Infectious Diseases of Humans: Dynamics and Control.* Oxford University Press, Oxford.

Andres, L. A., Thibert, M., Cordoba, C. L., Danilenko, A. V., Joseph, G., & Borja-Vega, C. (2019). *Doing More with Less: Smarter Subsidies for Water Supply and Sanitation*. World Bank, Washington, DC.

Arrow, K. J., Dasgupta, P., Goulder, L. H., Mumford, K. J., & Oleson, K. (2012). 'Sustainability and the measurement of wealth', *Environment and Development Economics*, 17/3: 317–53. DOI: 10.1017/S1355770X12000137

Arrow, K. J., Dasgupta, P., & Mäler, K. G. (2003). 'Evaluating Projects and Assessing Sustainable Development in Imperfect Economies', *Environmental and Resource Economics*, 26/4: 647–85. DOI: 10.1023/B:EARE.0000007353.78828.98

Balvanera, P., Pfisterer, A. B., Buchmann, N., He, J. S., Nakashizuka, T., Raffaelli, D., & Schmid, B. (2006). 'Quantifying the evidence for biodiversity effects on ecosystem functioning and services', *Ecology Letters*, 9/10: 1146–56. DOI: 10.1111/j.1461-0248.2006.00963.x

Bar-On, Y. M., Phillips, R., & Milo, R. (2018a). 'The biomass distribution on Earth', *Proceedings of the National Academy of Sciences of the United States of America*, 115/25: 6506–11. DOI: 10.1073/pnas.1711842115

Bar-On, Y. M., Phillips, R., & Milo, R. (2018b). 'The biomass distribution on Earth', *PNAS*. DOI: 10.1073/pnas.1711842115

Barbarossa, V., Schmitt, R. J. P., Huijbregts, M. A. J., Zarfl, C., King, H., & Schipper, A. M. (2020). 'Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide', *Proceedings of the National Academy of Sciences of the United States of America*, 117/7: 3648–55. DOI: 10.1073/pnas.1912776117

Barrett, S., Dasgupta, A., Dasgupta, P., Adger, W. N., Anderies, J., van den Bergh, J., Bledsoe, C., Bongaarts, J., Carpenter, S., Chapin, F. S., Crépin, A.-S., Daily, G., Ehrlich, P., Folke, C., Kautsky, N., Lambin, E. F., Levin, S. A., Mäler, K.-G., Naylor, R., et al. (2020). 'Social dimensions of fertility behavior and consumption patterns in the Anthropocene', *Proceedings of the National Academy of Sciences*, 117/12: 201909857. DOI: 10.1073/pnas.1909857117

Barro, R. B., & Sala-i-Martin, X. (2003). *Economic Growth*., Second Edi. The MIT Press, Cambridge, Massachussets: The MIT Press.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T. M., Evans, L. S., Kotschy, K., Leitch, A. M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M. D., Schoon, M. L., Schultz, L., & West, P. C. (2012). Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annual Review of Environment and Resources*, *37*(1), 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Bollinger, B., & Gillingham, K. (2012). 'Peer effects in the diffusion of solar photovoltaic panels', *Marketing Science*, 31/6: 900–12. DOI: 10.1287/mksc.1120.0727

Bongaarts, J., & Sinding, S. (2011). 'Population policy in transition in the developing world', *Science*, 333/6042: 574–6. DOI: 10.1126/science.1207558

Bourdieu, P. (1984). *Distinction: A Social Critique of the Judgement of Taste*. Harvard University Press, Cambridge, MA.

Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G. S., Limburg, K. E., Montes, I., Naqvi, S. W. A., Pitcher, G. C., Rabalais, N. N., Roman, M. R., Rose, K. A., Seibel, B. A., et al. (2018). 'Declining oxygen in the global ocean and coastal waters', *Science*, 359/6371. DOI: 10.1126/science.aam7240

Brundtland, G. H. (1987). Report of the World Commission on Environment and Development: Our Common Future.

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., & Kinzig, A. P. (2012). 'Biodiversity loss and its impact on humanity', *Nature*, 486/7401: 59–67. DOI: 10.1038/nature11148.Access

Chambers, J. Q., & Artaxo, P. (2017). 'Biosphere–atmosphere interactions: Deforestation size influences rainfall', *Nature Climate Change*, 7: 175–6. DOI: 10.1038/nclimate3238

CICES. (2018). 'CICES Version 5.1'. *CICES version 5.1*. Retrieved from <https://cices.eu/>

Cline, W. R. (1992). *The Economics of Global Warming*. Institute for International Economics, Washington, DC.

Coady, D., Parry, I., Le, N.-P., & Shang, B. (2019). *Global fossil fuel subsidies remain large. An update based on country-level estimates.* (No. 19/89). International Monetary Fund, Washington DC.

Daily, G. C. and Ehrlich, P. R. (1996) 'Global change and human susceptibility to disease', *Annual Review of Energy and the Environment*. doi: 10.1146/annurev.energy.21.1.125.

Dasgupta, A., & Dasgupta, P. (2017). 'Socially Embedded Preferences, Environmental Externalities, and Reproductive Rights', *Population and Development Review*, 43/3: 405–41. DOI: 10.1111/padr.12090

Dasgupta, P. (2004). *Human Well-Being and the Natural Environment*. (2nd Ed., Ed.). Oxford: Oxford University Press.

Dasgupta, P., & Maler, K.-G. (2000). 'Net national product, wealth, and social well-being', *Environment and Development Economics*, 5/1: 69–93. DOI: 10.1017/S1355770X00000061e

Dasgupta, P., & Ray, D. (1987). 'Inequality as a Determinant of Malnutrition and Unemployment: Policy', *The Economic Journal*, 97/385: 177–88.

Dasgupta, Partha. (1982). *The Control of Resources*. Cambridge, MA; Harvard University Press.

Dasgupta, Partha, Mitra, T., & Sorger, G. (2019). 'Harvesting the Commons', *Environmental and Resource Economics*, 72/3: 613–36. Springer Netherlands. DOI: 10.1007/s10640-018-0221-4

Dasgupta, Partha, & Ray, D. (1986). 'Inequality as a Determinant of Malnutrition and Unemployment: Theory', *The Economic Journal*, 96/384: 1011–34.

Debortoli, N. S., Dubreuil, V., Funatsu, B., Delahaye, F., Henke De Oliveira, C., Rodrigues-Filho, S., Carlos, &, Saito, H., & Fetter, R. (2015). 'Rainfall patterns in the Southern Amazon: a chronological perspective (1971-2010)', *Climatic Change*, 132: 251–64. DOI: 10.1007/s10584-015-1415-1

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., Hill, R., Chan, K. M. A., Baste, I. A., Brauman, K. A., Polasky, S., Church, A., Lonsdale, M., Larigauderie, A., Leadley, P. W., van Oudenhoven, A. P. E., van der Plaat, F., Schröter, M., Lavorel, S., et al. (2018). 'Assessing nature's contributions to people', *Science*, 359/6373: 270–2. DOI: 10.1126/science.aap8826

Ehrlich, P.R., & Ehrlich, A. H. (2008). *The Dominant Animal: Human Evolution and the Environment*. Washington DC: Island Press.

Ehrlich, Paul R., & Holdren, J. P. (1971). 'Impact of population growth', *Science*, 171/3977: 1212–7.

Estes, J. A., & Palmisano, J. F. (1974). 'Sea Otters: Their Role in Structuring Nearshore Communities', *Science*, 185/4156: 1058–60.

FAO. (2018). State of the World's Fisheries and Aquaculture - Meeting the Sustainable Development Goals. FAO, Rome.

——. (2019). The State of the World's Biodiversity for Food and Agriculture. FAO Commission on Genetic Resources for Food and Agriculture. DOI: 10.3233/epl-190136

Ferraro, P. J., & Price, M. K. (2013). 'Using nonpecuniary strategies to influence behavior: Evidence from a large-scale field experiment', *Review of Economics and Statistics*, 95/1: 64–73. DOI: 10.1162/REST_a_00344

Field, C.B., Behrenfeld, M. J., Anderson, J., & Falkowski, P. (1998). 'Primary Productivity of the Biosphere: Integrating Terrestrial and Oceanic Components', *Science*, 282: 237–40.

Field, Christopher B., Behrenfeld, M. J., Randerson, J. T., & Falkowski, P. (1998). 'Primary production of the biosphere: Integrating terrestrial and oceanic components', *Science*, 281/5374: 237–40. DOI: 10.1126/science.281.5374.237

Frank, R. H. (1997). 'The Frame of Reference as a Public Good', *The Economic Journal*, 107/445: 1832–47.

Galor, O. (2011). *Unified Growth Theory.* Princeton University Press, Princeton, New Jersey.

Garnett, E. E., Balmford, A., Sandbrook, C., Pilling, M. A., & Marteau, T. M. (2019). 'Impact of increasing vegetarian availability on meal selection and sales in cafeterias.', *Proceedings of the National Academy of Sciences of the United States of America*, 116/42: 20923–9. DOI: 10.1073/pnas.1907207116

Gonzalez, P., Neilson, R. P., Lenihan, J. M., & Drapek, R. J. (2010). 'Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change', *Global Ecology and Biogeography*, 19: 755–68.

Grollman, C., Cavallaro, F. L., Duclos, D., Bakare, V., Martínez, M., Lvarez, A. ´, & Borghi, J. (2018). 'Donor funding for family planning: levels and trends between 2003 and 2013', *574 Health Policy and Planning*, 33: 574–82. DOI: 10.1093/heapol/czy006

Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., Lovejoy, T. E., Sexton, J. O., Austin, M. P., Collins, C. D., Cook, W. M., Damschen, E. I., Ewers, R. M., Foster, B. L., Jenkins, C. N., King, A. J., Laurance, W. F., Levey, D. J., Margules, C. R., et al. (2015). 'Habitat fragmentation and its lasting impact on Earth's ecosystems', *Science Advances*, 1/2: 1–10. DOI: 10.1126/sciadv.1500052

Hamilton, K., & Clemens, M. (1999). 'Genuine savings rates in developing countries', *World Bank Economic Review*, 13/2: 333–56. DOI: 10.1093/wber/13.2.333

Hardin, G. (1968). 'The Tragedy of the Commons', *Science*, 162: 1243–8.

Harrison, P. A., Berry, P. M., Simpson, G., Haslett, J. R., Blicharska, M., Bucur, M., Dunford, R., Egoh, B., Garcia-Llorente, M., Geamănă, N., Geertsema, W., Lommelen, E., Meiresonne, L., & Turkelboom, F. (2014). 'Linkages between biodiversity attributes and ecosystem services: A systematic review', *Ecosystem Services*, 9: 191–203. DOI: 10.1016/j.ecoser.2014.05.006

Helpman, E. (2004). *The Mystery of Economic Growth*. Harvard University Press, Cambridge, MA.

Herweijer, C., Combes, B., Ramchandani, P., & Sidhu, J. (2018). 'Fourth Industrial Revolution for the Earth: Harnessing Artificial Intelligence for the Earth', January.

Hollands, G. J., Cartwright, E., Pilling, M., Pechey, R., Vasiljevic, M., Jebb, S. A., & Marteau, T. M. (2018). 'Impact of reducing portion sizes in worksite cafeterias: a stepped wedge randomised controlled pilot trial', *International Journal of Behavioral Nutrition and Physical Activity*, 15/78. DOI: 10.1186/s12966-018-0705-1

Houghton, R. A., Byers, B., & Nassikas, A. A. (2015). 'A role for tropical forests in stabilizing atmospheric CO2', *Nature Climate Change*, 5/12: 1022–3. Nature Publishing Group. DOI: 10.1038/nclimate2869

IPBES (2019): Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. S. Díaz, J. Settele, E. S. Brondízio E.S., H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, A. Pfaff, S. Polasky, A. Purvis, J. Razzaque, B. Reyers, R. Roy Chowdhury, Y. J. Shin, I. J. Visseren-Hamakers, K. J. Willis, and C. N. Zayas (eds.). IPBES secretariat, Bonn, Germany. 56

IPCC. (2015). *Climate Change 2014: Synthesis Report*. DOI: 10.1021/om00044a023

Jones, K. E., Patel, N. G., Levy, M. A., Storeygard, A., Balk, D., Gittleman, J. L., & Daszak, P. (2008). 'Global trends in emerging infectious diseases', *Nature*, 451/7181: 990–3. DOI: 10.1038/nature06536

Jorda, O., Knoll, K., Kuvshinov, D., Moritz Schularick, Z., & Taylor, A. M. (2019a). *The Rate of Return on Everything*. *NBER Working Paper*, Vol. 24112. Retrieved from <https://www.nber.org/papers/w24112>

——. (2019b). The Rate of Return on Everything. NBER Working Paper, Vol. 24112.

Kareiva, P., Tallis, H., Ricketts, T. R., Daily, G. C., & Polasky, S. (2011). *Natural Capital: The Theory and Practice of Mapping Ecosystem Services*. Oxford University Press, Oxford: Oxford University Press.

Kaya, Y., & Yokobori, K. (1997). Environment, Energy and Economy: Strategies for Sustainability. Tokyo.

Kohler, H.-P., Behrman, J. R., & Watkins, S. C. (2001). 'The Density of Social Networks and Fertility Decisions: Evidence from South Nyanza District, Kenya', *Demography*, 38/1: 58.

Kousky, C., & Light, S. E. (2019). 'Insuring Nature', *Duke Law Journal*, 69: 323–76.

Kumar, P. (2010). The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundation. Earthscan, London and Washington DC.

Laffoley, D., & Baxter, J. M. (2019). Ocean deoxygenation: Everyone's problem - Causes, impacts, consequences and solutions. IUCN, Gland, Switzerland.

Laurance, W. F., Lovejoy, T. E., Vasconcelos, H. L., Bruna, E. M., Didham, R. K., Stouffer, P. C., Gascon, C., Bierregaard, R. O., Laurance, S. G., & Sampaio, E. (2002). 'Ecosystem Decay of Amazonian Forest Fragments: A 22-Year Investigation', *Conservation Biology*, 16/3: 605–18.

Law, Y.-H. (2020). 'Wild Bees are in Decline Globally', *Science News*, February 1.

Levin, S. (1999). *Fragile Dominion: Complexity and the Commons*. Reading, MA.: Helix. DOI: 10.1017/S1355770X0422160X

Little, I. M., & Mirrlees, J. A. (1974). *Project Appraisal and Planning for Developing Countries*. London, Heinemann Educational Books.

Loh, E. H., Olival, K. J., Zambrana-Torellio, C., Bogich, T. L., Johnson, C. K., Mazet, J. A. K., Karesh, W. B., & Daszak, P. (2015). 'Targeting transmission patheways for emerging zoonotic disease surveillance and control.', *Vector Borne and Zoonotic Diseases*, 15/7.

Lomborg, B. (ed.) (2013) *How Much have Global Problems Cost the World?* Cambridge: Cambridge University Press. doi: 10.1017/CBO9781139225793.

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J. P., Hector, A., Hooper, D. U., Huston, M. A., Raffaelli, D., Schmid, B., Tilman, D., & Wardle, D. A. (2001). 'Ecology: Biodiversity and ecosystem functioning: Current knowledge and future challenges', *Science*, 294/5543: 804–8. DOI: 10.1126/science.1064088

Lovejoy, T. E., & Hannah, L. (2019). Biodiversity and climate change: Transforming the biosphere. Biodiversity and Climate Change: Transforming the Biosphere. Yale University Press.

Lovejoy, T., & Nobre, C. (2019). 'Amazon tipping point: Last chance for action', *Science Advances*, 5. DOI: 10.1126/sciadv.aba2949

Lovejoy, T. E. and Nobre, C. (2018) 'Amazon tipping point', *Science Advances*. American Association for the Advancement of Science, p. eaat2340. doi: 10.1126/sciadv.aat2340.

Managi, S., & Kumar, P. (2018). *Inclusive Wealth Report 2018*. London. DOI: https://doi-org.stanford.idm.oclc.org/10.4324/9781351002080

Millennium Ecosystem Assessment. (2005). *Ecosystems and Human Wellbeing: Biodiversity Synthesis*. World Resources Institute, Washington DC.

Mitsch, W. J., & Jorgensen, S. E. (1989). 'Ecological Engineering: An Introduction to Ecotechnology'. Mitsch W. J. & Jorgensen S. E. (eds). John Wiley & Sons, New York.

Morikawa, M. K., & Palumbi, S. R. (2019). 'Using naturally occurring climate resilient corals to construct bleaching-resistant nurseries', *Proceedings of the National Academy of Sciences of the United States of America*, 116/21: 10586–91. DOI: 10.1073/pnas.1721415116

Munshi, K., & Myaux, J. (2006). 'Social norms and the fertility transition', *Journal of Development Economics*, 80: 1–38. DOI: 10.1016/j.jdeveco.2005.01.002

Natural Capital Coalition. (2016). *Natural capital Protocol*. DOI: 10.1017/s1358246100006536

Newbold, T. (2018). 'Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios', *Proceedings of the Royal Society B: Biological Sciences*, 285/1881. DOI: 10.1098/rspb.2018.0792

Norberg, Johan (2016). Progress. Ten reasons to look forward to the future' (2017) *International Journal on Food System Dynamics*. doi: 10.18461/ijfsd.v8i2.828.

Nordhaus, W. D. (1994). Managing the Global Commons: The Economics of Climate Change. MIT Press, Cambridge, MA.

OECD. (2017). *Reforming agricultural subsidies to support biodiversity in Switzerland* (No. 8). OECD Environment Policy Paper. Retrieved from

<https://www.oecd.org/environment/resources/Policy-Paper-Reforming-agricultural-subsidies-to-support-biodiversity-in-Switzerland.pdf>

——. (2020). 'A Comprehensive Overview of Global Biodiversity Finance'.

Oliveras, I., & Malhi, Y. (2016). 'Many shades of green: The dynamic tropical forest–savannah transition zones'. *Philosophical Transactions of the Royal Society B: Biological Sciences*. Royal Society of London. DOI: 10.1098/rstb.2015.0308

Orgiazzi, A., Bardgett, R. D., Barrios, E., Behan-Pelletier, V., Briones, M. J. I., Chotte, J.-L., De Deyn, G. B., Eggleton, P., Fierer, N., Fraser, T., Hedlund, K., Jeffery, S., Johnson, N. C., Jones, A., Kandeler, E., Kaneko, N., Lavelle, P., Lemanceau, P., Miko, L., et al. (2016). *Global Soil Biodiversity Atlas*. Luxembourg: Publications Office of the European Union.

Ostrom, E. (2010) 'Polycentric systems for coping with collective action and global environmental change', *Global Environmental Change*. Elsevier Ltd, 20(4), pp. 550–557. doi: 10.1016/j.gloenvcha.2010.07.004.

Patz, J. A., Graczyk, T. K., Geller, N., & Vittor, A. H. (2000). 'Effects of environmental change on emerging parasitic diseases.', *International journal for parasitology*, 30/12: 1395–405.

Perrings, C. (2014). *Our Uncommon Heritage*. Cambridge University Press, Cambridge, UK.

Pimm, S. L., Jenkins, C. N., Abell, R., Brooks, T. M., Gittleman, J. L., Joppa, L. N., Raven, P. H., Roberts, C. M., & Sexton, J. O. (2014). 'The biodiversity of species and their rates of extinction, distribution, and protection', *Science*, 344/6187. DOI: 10.1126/science.1246752

Pimm, Stuart L., & Raven, P. H. (2019). 'The State of the World's Biodiversity'. *Biological Extinction: New Perspectives*, pp. 80–112. DOI: 10.1017/9781108668675.006

Pinker, S. (2018). *Enlightenment Now: The Case for Reason, Science, Humanism, and Progress.* Viking.

Potts, S. G., Imperatriz-Fonseca, V. L., Ngo, H. T., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J., Vanbergen, A. J., Aizen, M. A., Cunningham, S. A., Eardley, C., Freitas, B. M., Gallai, N., Kevan, P. G., Kovacs-Hostyanszki, A., Kwapong, P. K., Li, J., et al. (2016). *Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production.* Bonn, Germany. DOI: 10.1007/s00442-010-1809-8

Ridley, M. (2012) 'The Rational Optimist: How Prosperity Evolves', *Brock Education Journal*. doi: 10.26522/brocked.v21i2.280.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., et al. (2009). 'A safe operating space for humanity', *Nature*, 461/September.

Scheffer, M. (2009). *Critical Transitions in Nature and Society*. Princeton, NJ: Princeton University Press.

Scheffer, M., & Carpenter, S. R. (2003). 'Catastrophic regime shifts in ecosystems: linking theory to observation', *TRENDS in Ecology and Evolution*, 18/12. DOI: 10.1016/j.tree.2003.09.002

Scheffer, M., Carpenter, S. R., Lenton, T. M., Bascompte, J., Brock, W., Dakos, V., Van De Koppel, J., Van De Leemput, I. A., Levin, S. A., Van Nes, E. H., Pascual, M., & Vandermeer, J. (2012). 'Anticipating Critical Transitions', *Science*, 338/6105: 344–8.

Sodhi, N. S., Brook, B. W., & Bradshaw, C. J. A. (2009). 'Causes and consequences of species extinctions'. Levin, S.A. et al. E. (ed.) *The Princeton Guide to Ecology*. Princeton, NJ: Princeton University Press.

Solow, R. (1963). *Capital Theory and the Rate of Return*. North-Holland Publishing Company.

Steffen, W., Andreae, M. O., Bolin, B., Cox, P. M., Crutzen, P. J., Cubasch, U., Held, H., Nakicenovic, N., Talaue-Mcmanus, L. T., & Turner, B. L. I. (2004). *Group Report: Earth System Dynamics in the Anthropocene*.

Steffen, Will, Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). 'The trajectory of the anthropocene: The great acceleration', *Anthropocene Review*, 2/1: 81–98. DOI: 10.1177/2053019614564785

Steffen, Will, Grinevald, J., Crutzen, P., & Mcneill, J. (2011). 'The anthropocene: Conceptual and historical perspectives', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369/1938: 842–67. DOI: 10.1098/rsta.2010.0327

Steffen, Will, Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries, W. De, Wit, C. A. De, Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). 'Planetary boundaries: Guiding human development on a changing planet', *Science*, 347/6223: 1–10. DOI: 10.1126/science.1259855

Steffen, Will, Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., & Schellnhuber, H. J. (2018). 'Trajectories of the Earth System in the Anthropocene', *Proceedings of the National Academy of Sciences of the United States of America*, 115/33: 8252–9. DOI: 10.1073/pnas.1810141115

Stern, N. (2006). *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge.

Sukhdev, P.; Wittmer, H.; Miller, D. (2014). The Economics of Ecosystems and Biodiversity (TEEB): Challenges and responses. Nature in the Balance: The Economics of Biodiversity. Oxford.

Thomas, R., & Dimsdale, N. (2017). *A millennium of macroeconomic data*. Bank of England OBRA dataset.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D., & Swackhamer, D. (2001).

‘Forecasting agriculturally driven global environmental change’, *Science*, 292/5515: 281–4. American Association for the Advancement of Science. DOI: 10.1126/science.1057544

Tilman, D., Isbell, F., & Cowles, J. M. (2014). ‘Biodiversity and Ecosystem Functioning’, *Annu. Rev. Ecol. Evol. Syst*, 45: 471–93. DOI: 10.1146/annurev-ecolsys-120213-091917

UK Natural Capital Committee. (2020). Natural Capital Committee’s Seventh annual report.

UN Population Division. (2019). World Population Prospects 2019 Highlights.

UNU/IHDP-UNEP. (2015). *Inclusive Wealth Report 2014*. Cambridge University Press, Cambridge.

Voosen, P. (2016). ‘Anthropocene pinned to postwar period’, *Science*, 353/6302: 852–3. DOI: 10.1126/science.353.6302.852

De Vos, J. M., Joppa, L. N., Gittleman, J. L., Stephens, P. R., & Pimm, S. L. (2015). ‘Estimating the normal background rate of species extinction’, *Conservation Biology*, 29/2: 452–62. DOI: 10.1111/cobi.12380

Wackernagel, M., & Beyers, B. (2019). *Ecological footprint: managing our biocapacity budget*. Gabriola Island, BC Canada: New Society.

Waters, C. N., Steffen, W., Waters, C. N., Zalasiewicz, J., Zalasiewicz, J., Summerhayes, C., Summerhayes, C., Barnosky, A. D., Barnosky, A. D., Poirier, C., Poirier, C., Ga, A., Ga uszka, A., Cearreta, A., Cearreta, A., Edgeworth, M., Edgeworth, M., Ellis, E. C., Ellis, E. C., et al. (2016). ‘The Anthropocene is functionally and stratigraphically distinct from the Holocene’, *Science*, 351/6269: aad2622–aad2622.

Wooldridge, A. and Micklethwait, J. (2001) A Future Perfect: The Challenge and Hidden Promise of Globalization, Harvard Business Review. doi: GLOB MICK.

World Bank. (2018). ‘World Development Indicators’. Retrieved April 2, 2020, from <http://datatopics.worldbank.org/world-development-indicators/>

World Economic Forum. (2020). ‘The Global Risks Report 2020’, 1–114.

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C., Lotze, H. K., Micheli, F., Palumbi, S. R., Sala, E., Selkoe, K. A., Stachowicz, J. J., & Watson, R. (2006). ‘Impacts of biodiversity loss on ocean ecosystem services’, *Science*, 314/5800: 787–90. DOI: 10.1126/science.1132294

WWF. (2018). Living Planet Report.

**HM Treasury contacts**

This document can be downloaded from
www.gov.uk

If you require this information in an alternative format or have general enquiries about HM Treasury and its work, contact:

Correspondence Team
HM Treasury
1 Horse Guards Road
London
SW1A 2HQ

Tel: 020 7270 5000

Email: public.enquiries@hmtreasury.gov.uk