Eroding Natural Capital: An Alternative Explanation for the Secular Decline in Productivity Growth

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Abstract

Labour productivity and multifactor productivity (MFP) growth rates have been declining in advanced economies for several decades, and the decline in labour productivity growth has extended to emerging economies over the past fifteen years. Global MFP growth has flatlined since 2007 in both advanced and emerging economies. While many explanations for these trends have been advanced, no clear consensus has yet emerged. However, the pervasive and persistent nature of the declines signals that factors of global scope and extended duration are likely implicated. This article presents an alternative explanation for declining productivity growth: that the erosion of natural capital has been occurring on a sufficiently large scale globally to exert significant and growing downward pressure on productivity growth. Accordingly, a fundamental transformation in the economic role of natural capital has taken place, from productivity accelerator to productivity decelerator. These effects have been obscured due to the absence of natural capital from conventional economic frameworks and production functions.

This article sets out an alternative to the prevailing explanations for the ongoing secular decline in productivity growth rates – namely, that eroding natural capital has been exerting consistent and prolonged downward pressure on global productivity growth.

Labour productivity growth rates have exhibited a declining trend in advanced economies for several decades; over the past fifteen years, this trend has extended to emerging and developing economies (Charts 1 and 2).

Much of the long-term decline in labour productivity growth has been attributed to a corresponding slowing of multifactor productivity (MFP) growth (Bergeaud *et al.*, 2018; Dieppe, 2021; Moss *et al.*, 2020).

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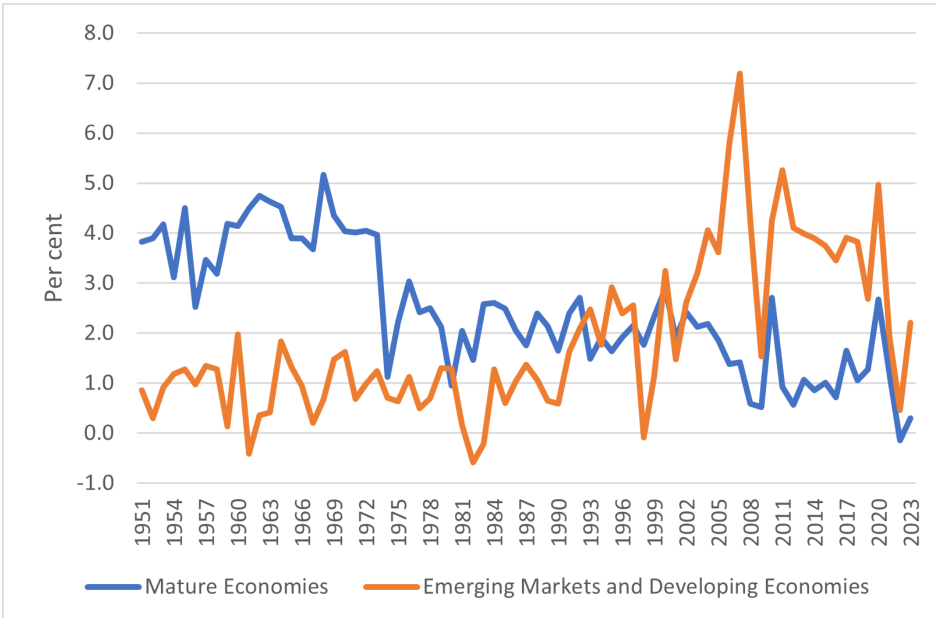
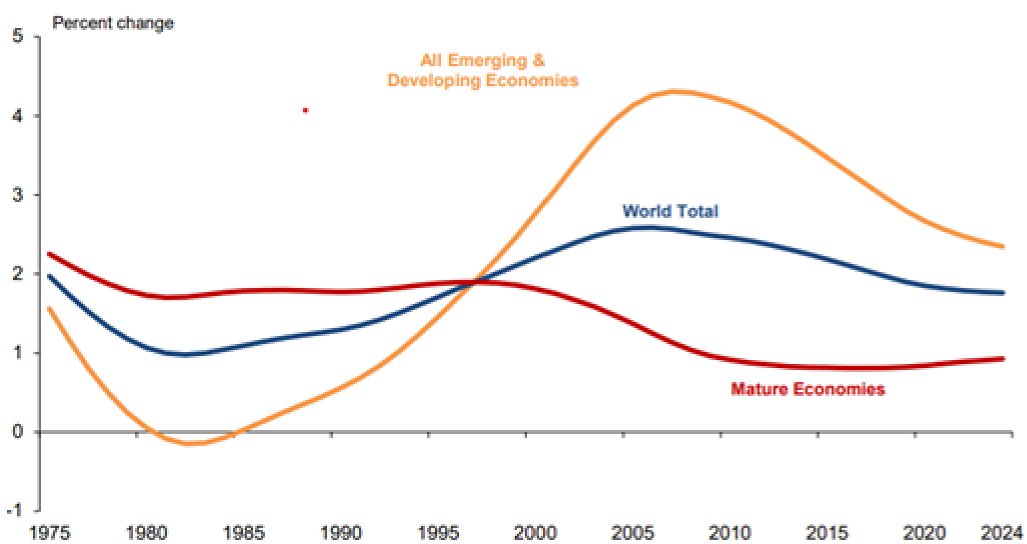
Chart 1: Hourly Labour Productivity in Mature and Emerging Market and Developing Economies, 1951-2023 (annual per cent change)



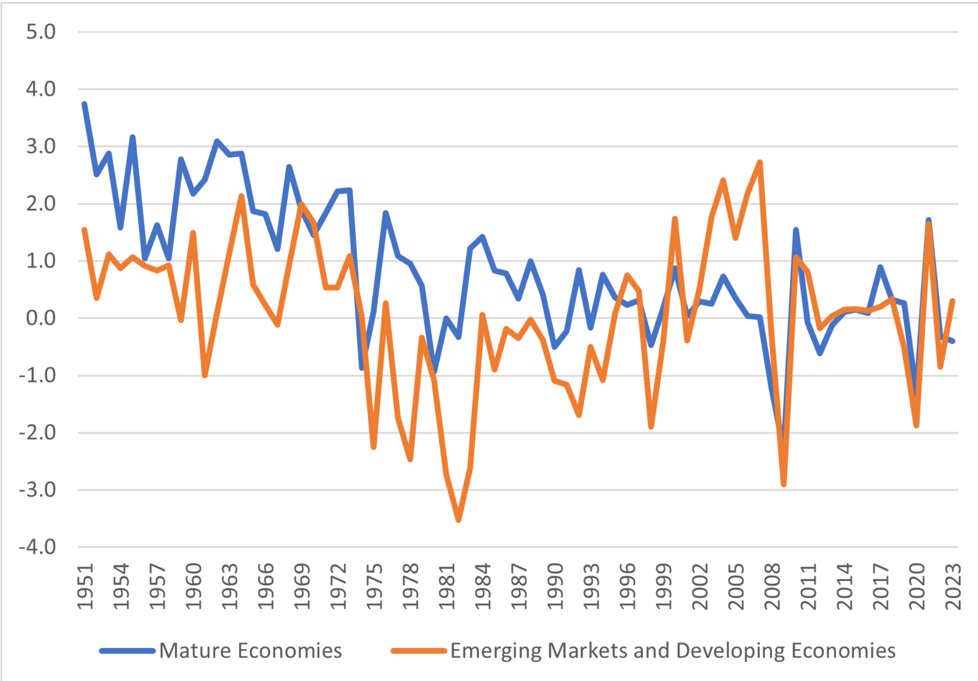
Source: The Conference Board Total Economy Database (TED)

Chart 2: Trend growth in GDP Per Person Employed, Mature and Emerging Market and Developing Economies, 1975-2024



Note: Trend growth rates obtained using HP filter, assuming lambda=100
Source: The Conference Board (2024)

Chart 3: Annual Growth in Total Factor Productivity, Mature and Emerging Market and Developing Economies, 1951-2023 Change in natural log



Source: The Conference Board Total Economy Database

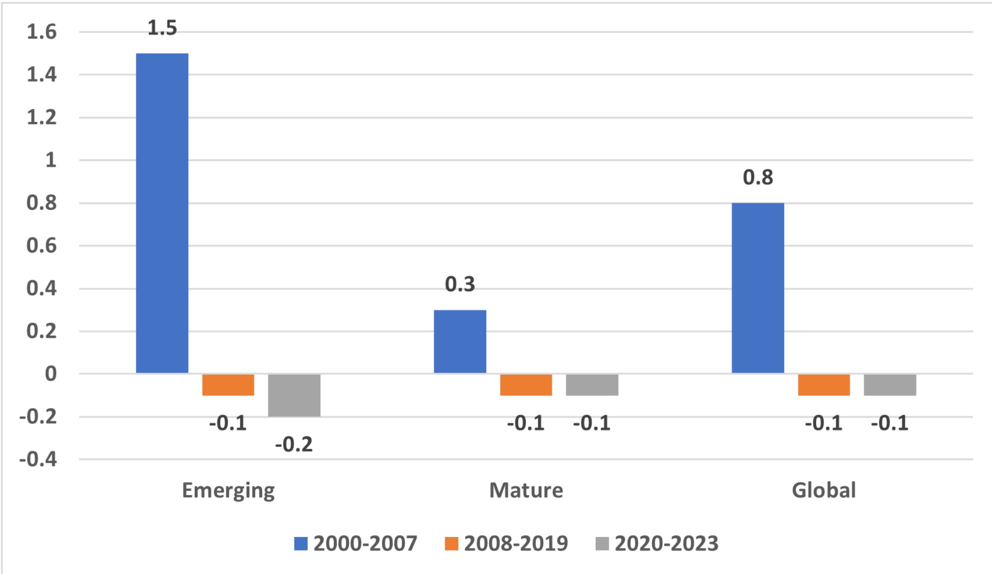
In advanced economies, while there have been periodic surges – such as the US turn-of-the-century bounce widely attributed to the impact of the information and communication technology (ICT) revolution, and the rebound following the 2008-09 global recession – the underlying MFP/Total Factor Productivity (TFP) trend has been downward (Chart 3).[2] MFP growth in major advanced economies between 1890 and 2015 has been trending down since the 1940s in the United States, the 1950s for the Euro area, the 1960s for Japan and the 1980s for the UK, following WWII and post-WWII booms, with ensuing declines from peak growth rates of between 2 per cent and 5 per cent to less than 1 per cent (Bergeaud *et al.*, 2017). In emerging and developing economies, MFP growth has been in negative territory for most of the past fifty years, with the exception of the decade preceding the 2008-09 financial crisis.

Global MFP growth has essentially flat-lined since 2007 and even moved into marginally negative territory, averaging -0.1 per cent between 2008 and 2023, with negative average growth in both emerging and mature economies (Chart 4).

Productivity growth is at the core of our prosperity and underpins any improvement in measured living standards. These trends are therefore of significant concern, particularly as the demographic dividend

2 As the terms multifactor productivity (MFP) and total factor productivity (TFP) refer to the same essential concept, they are used interchangeably in this article.

Chart 4: Total Factor Productivity Growth, 2000-2023: Global, Emerging and Mature Economies Average Annual Growth (Per cent)



Source: The Conference Board Total Economy Database (2024)

that boosted production for many years has come to an end in most advanced economies and some emerging ones. The global flatlining of MFP growth raises particular issues as, in its absence, real economic growth can be achieved only by continued intensification of inputs.

A wide range of explanations have been advanced for the secular declines in labour productivity and MFP growth. Some of the more prominent are: the demise of transformative innovation following the first and second industrial revolutions (Gordon, 2012, 2013); lags between innovations and their widespread adoption (Brynjolfsson *et al.*, 2018); sectoral shifts (Borio *et al.*, 2016); mismeasurement (Byrne *et al.*, 2016); and insufficient aggregate demand (Summers, 2015). Despite extensive analysis and debate, no clear consensus has emerged. However, the pervasive and persistent nature of the declines and stagnation across advanced economies and emerging economies signals that factors of global scope and extended duration are likely implicated.

This article sets out an alternative explanation for declining labour productivity and MFP growth. It proposes that ongoing loss of natural capital, including progressive loss of climate stability, has become a significant driver of declining productivity growth over the past several decades. The key elements of this argument are:

- Scientific evidence indicates that human activities have resulted in significant depletion of natural resources and damage to ecosystems and that these impacts have accelerated rapidly in recent decades, progressively outstripping the regenerative capacity of natural systems.
- These findings have been translated into economic terms through the development of increasingly sophisticated measurements of natural capital; the most comprehensive of these measures, produced by the United

Nations Environment Program (UNEP), shows correspondingly large global declines in natural capital.

- Numerous transmission channels translate natural capital erosion into productivity declines.
- A rapidly growing literature provides substantial evidence of direct connections between damage to natural capital and significant negative impacts to productivity in a wide range of industries and locations.
- In aggregate, these impacts have become sufficiently large over the past half century as to constitute a significant, ongoing and likely growing depressor of productivity growth.
- Accordingly, a fundamental transformation in the economic role of natural capital occurred in the second half of the 20th century, from productivity booster to productivity decelerator.
- As conventional economic frameworks and production functions do not include natural capital, these impacts are often obscured.
- Additional declines in natural capital are likely to depress productivity growth further.

The case for this argument is set out in the balance of this article, as follows. Section 1 examines natural capital and its link to productivity, including: how that relationship changed in the latter half of the 20th century; measured declines in natural capital; transmission channels from these declines to productivity; and insights from the growing literature on this topic. Section 2 reviews the scientific evidence on the deterioration of natural capital in four key areas: climate change; biodiversity loss; soil and sub-soil resource depletion; and waste, pollution and contamination. Section 3 examines the growing body of evidence on how deteriorating natural capital in these areas has translated into significant productivity declines worldwide. Section 4 summarizes these findings and offers some concluding thoughts.

Natural Capital and Its Link to Productivity

The term "natural capital" was introduced by Schumacher, who asserted that natural capital stocks account for the largest part of all capital (Schumacher, 1973). The foundation of all economies is natural capital, defined here in alignment with the United Nations Environment Program (UNEP) as the stocks of environmental assets (including natural resources, ecosystems and a stable climate) that generate flows of goods and services into the economy (UNEP, 2023). Economies are deeply embedded in natural systems and extensively reliant on inputs of natural resources. Natural resources include all resources, living and abiotic, renewable and nonrenewable, such as soil, water, forests, plants, fish, air, wildlife, minerals and fossil fuels. Ecosystem services include processes such as oxygen generation, rainfall, pollination, carbon storage, flood protection, air and water filtration, waste decomposition, climate regulation and climate stability, and habitat provision for fisheries and wildlife.

Production – and hence productivity – is clearly heavily reliant on natural systems and resources. This is most evident in the primary sector: agriculture relies on arable soil, seeds, rain, stable climate, plants and animals, and pollination services; fisheries on the presence of fish populations and habitat; mining on mineral deposits; and forestry on the presence of trees and forests. Manufacturing industries have traditionally been primarily powered by energy from fossil fuels and require metals, minerals and other natural resources as inputs. Similarly, construction is dependent on materials such as timber, stone, sand, limestone and metals. Ecosystem services provide the basic support services for all life and are therefore the essential underpinning for all human activities. Stable and predictable climate, with minimal extreme weather, is essential to many economic activities.

Two recent assessments determined that over half (55 per cent) of global GDP is generated by industries that are completely, highly or moderately dependent on nature (Evison, 2023; Swiss Re, 2020). Industries with less direct dependence on nature show significant indirect dependencies through supply chains (World Economic Forum, 2020).

Despite the fundamental nature of natural capital as the basis for all economic activity, conventional economic frameworks do not typically include it as a factor of production.[3] This is largely for two reasons. First, natural capital was traditionally regarded as effectively limitless, unchanging and impervious to human actions, and therefore as a 'given' endowment.

Second, the value of natural capital has often not been monetized or included in market transactions, except where appropriated through private ownership. It was therefore difficult to measure[4] and has generally been treated as a 'free' public good.[5] Because natural capital has traditionally not been viewed as a productive capital asset, its role in the economy has often been invisible and thus devalued, giving rise to significant externalities and distorted economic incentives. Because it was seen as a gift of nature, it was often overexploited, as the benefits associated with its exploitation largely accrued privately, while the external costs from overuse were publicly shared.

Natural Capital: From Productivity Driver to Productivity Depressor

How has the relationship between natural capital and productivity growth changed, and why? This article proposes that a fundamental transformation in the economic role of natural capital occurred during the 20th century, from productivity booster to productivity drag. Expanding access to and use of natural capital was a key driver of productivity growth for at least three centuries prior to the mid-20th century. Increasing travel and trade expanded access to the resources available for

3 Natural capital has not always been excluded; the physiocrats and classical economists treated land as a factor of production.

4 Dasgupta notes that much natural capital is mobile, silent and invisible, further complicating its measurement (Dasgupta, 2021).

5 The two key attributes of a public good are non-rivalry (i.e. the cost of extending output to an additional person is zero) and non-exclusion (i.e. it is impossible to exclude individuals from benefiting from it).

economic production; and energy derived from fossil fuels fueled industrial and infrastructure growth and enabled the development of new technologies.

However, sometime after the middle of the 20th century, an inflection point emerged. The demands of human economic activity began to progressively surpass Earth's regenerative capacity – that is, we collectively began to run a natural capital deficit, with ensuing declines in natural capital stocks. Since that point, accumulated and accelerating damage to the natural capital foundation of all economies has slowed productivity growth, and the role of natural capital has shifted from productivity driver to productivity decelerator. The erosion of natural capital reached sufficient magnitude to exert significant and growing downward pressure on productivity growth.

This sea change can be described as a transition from what was long viewed as an 'open' economic system – a frontier economy where the consequences of localized resource depletion or ecosystem damage could often be avoided by moving on to greener pastures – to a closed system – a spaceship economy – where planetary limits have become increasingly apparent.[6]

Prior to the middle of the 20th century, two key factors operating in tandem with innovation enabled the growth of market economies: the huge de facto expansion of natural resource availability afforded, first, by colonization and, later, by growth in international trade; and the vast energy derived from fossil fuels. Colonization and imperialism freed European market economies from domestic resource constraints by vastly expanding the scope and reach of resource availability, enabling economic growth that would not otherwise have been possible.[7] The transition to fossil fuels – first coal, then oil and gas – was the other enabler of the surges of economic growth generated by the first and second industrial revolutions.[8]

Indeed, all of the key Industrial Revolution innovations relied on fossil fuels. The first Industrial Revolution (1770-1840) required coal power for cotton ginnies, railroad engines and steamships, while the second (1870-1920) relied on a range of fossil fuels – gasoline to power internal combustion engines, coal and gas to generate electricity, and fossil fuel inputs for fertilizer and chemical production. This expanded energy access was essentially inseparable from the technological advances of the period as instrumental in spurring waves of productivity growth.[9] Between 1800 and 2000 global population grew six-fold, energy use forty-fold and the global economy

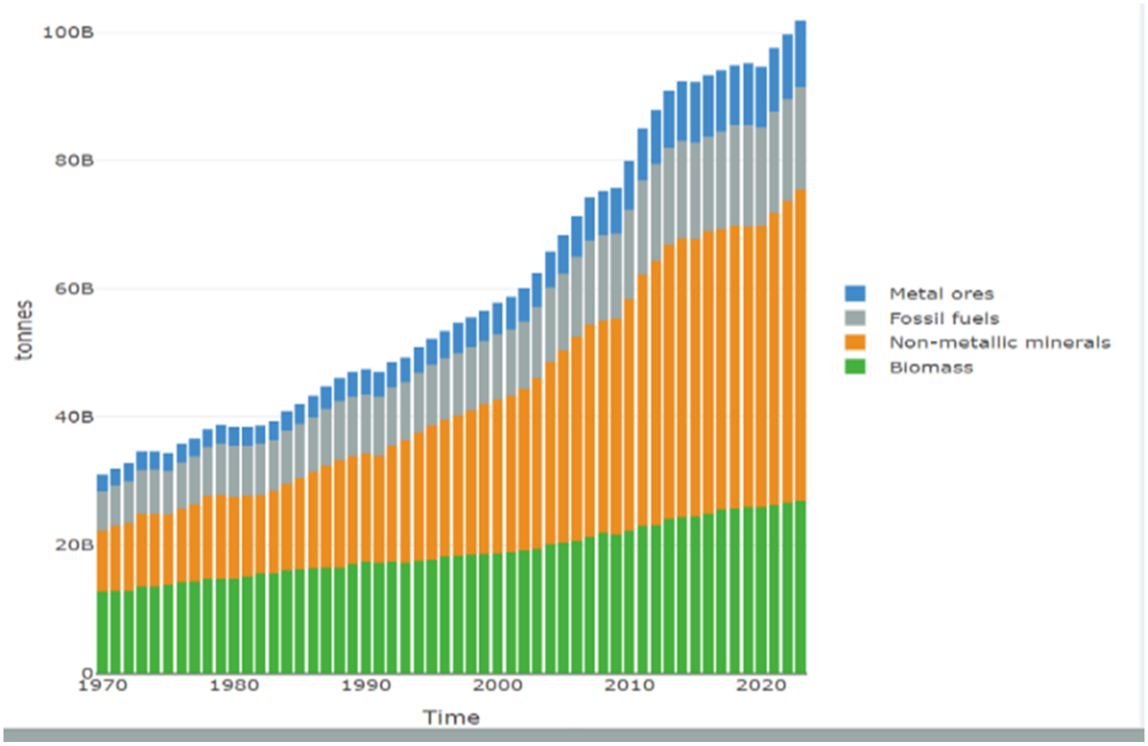
6 This transition was described by Kenneth Boulding, who used the terms 'cowboy economy' and 'spaceman economy' (Boulding, 1973).

7 Instances of local and regional depletion of natural capital, with sometimes acute economic consequences, have been documented by authors including Diamond (2005), Frankopan (2023) and Wright (2004).

8 A third factor, slavery, also expanded output on the basis of human suffering, but is outside the focus of this article.

9 The links between energy and economic growth during this period have been documented by economists and economic historians including: Elkomy *et al.* (2020); Frankopan (2023); Stern and Kander (2012); and Wrigley (2010).

Chart 5: Global Material Extraction by Type, 1970-2023



Source: Vienna University (2024)

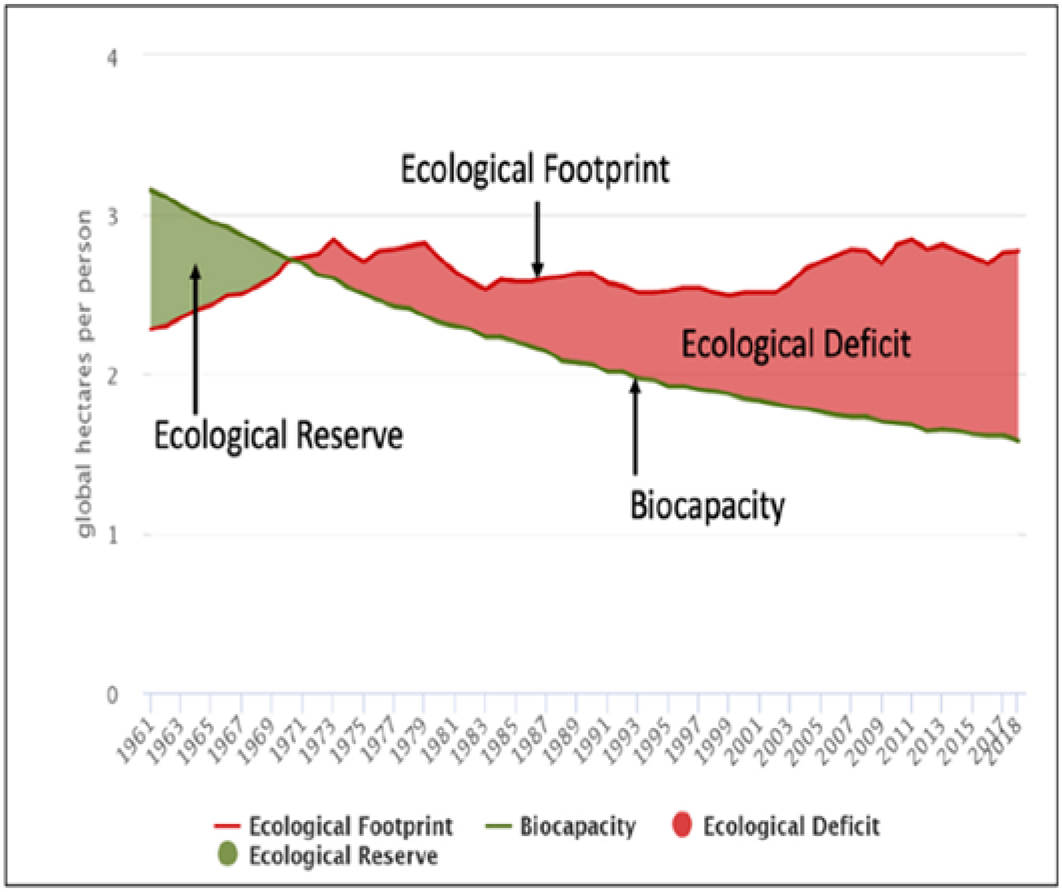
fifty-fold (Steffen *et al.*, 2008).

Erosion of natural capital took place on a relatively modest scale in the frontier economy. The global population and economy were much smaller, most waste was organic, and the destructive impacts of accumulating greenhouse gas (GHG) emissions were not yet apparent. Damage to the natural environment occurred, but often on a local or regional rather than global scale that permitted a degree of regeneration of natural systems. The economic benefits of growing natural capital usage, which largely accrued privately, apparently outweighed the shared costs of environmental damage.

However, accumulating evidence indicates that at some point in the latter half of the 20th century the rapidly expanding scale of human impacts on the natural environment began to outstrip the capacity of natural systems for regeneration. Since the early 1970s the demands of human economic activity on the environment have accelerated rapidly: global population has doubled, world GDP quadrupled and global trade grown tenfold (IPBES, 2019). Global material extraction has more than tripled, from 31 to 102 billion tonnes (Gt) annually (Chart 5), with significant related environmental impacts from both its extraction and subsequent disposal.[10]

10 The increase in global material extraction since 1970 has been driven in approximately equal parts by population growth and growth in GDP per capita; technological change has acted to partially offset these drivers (UNEP, 2024).

Chart 6: Global Ecological Footprint and Biocapacity per Capita



Source: P. Victor (2023) and York University Ecological Footprint Initiative and Global Footprint Network (2022)

Environmental footprint analysis compares Earth's biocapacity – the ability of ecosystems to regenerate – with the demands placed on it by humans (Wackernagel and Rees, 1995). It indicates that humans collectively began to exceed the ability of Earth to provide resources sustainably around 1970, and now annually use 75 per cent more than what Earth can sustainably provide (WWF, 2022). Chart 6 graphs the human environmental footprint per capita against Earth's biocapacity per capita. It shows that prior to 1970 Earth's biocapacity exceeded the demands made on it, i.e. there was an 'ecological reserve', but since then, human demands have exceeded Earth's biocapacity by a growing margin, resulting in an expanding 'ecological deficit'.[11]

Nobel Laureate Paul Crutzen observed that by the second half of the 20th century the planetary impacts of human activities had begun to outrival those of natural forces, and he accordingly proposed that Earth had entered a new geological epoch, the Anthropocene (Steffen *et al.*,

11 Both Earth's biocapacity and humanity's environmental footprint can expand or contract.

2008). Others have endorsed this view, finding that multiple indicators provide evidence of a 'great acceleration' since mid-century in the impact of humans on the planet (IPBES, 2020; Steffen *et al.*, 2015).

The planetary boundaries framework, developed by an international team of scientists to identify a safe operating space for human life, identified nine key systems critical to the stability of the Earth system, and respective safe operating boundaries for each. By 2023, six of the nine – climate change, biosphere integrity, land system change, change in freshwater cycles, synthetic pollutants, and biogeochemical flows – had transgressed safe limits, leading the scientists to conclude that Earth is now "well outside of the safe operating space for humanity" (Richardson *et al.*, 2023). By 2024 a seventh system, ocean acidification, was close to breaching the boundary, leaving only two – ozone depletion and atmospheric loading – well within the safe boundaries (Caesar *et al.*, 2024).

The 350 ppm atmospheric carbon dioxide level associated with maintaining a relatively stable global climate was breached in 1990, and the impacts of climate change have subsequently intensified and accelerated (IPCC, 2023). Over two thirds of Earth's global temperature increase of nearly 1.5° C has occurred since 1980.

Strong productivity growth was maintained for an extended period of time, then, in large part by reliance on fossil fuels – at the eventual expense of a stable climate – and by depletion of other resources. When natural systems were eventually stretched beyond the limits of sustainability, we began to run a collective natural capital deficit, with human demands exceeding Earth's regenerative capacity. Net natural capital depletion became a growing drag on productivity growth, reducing the quantity and quality of goods and services provided by the natural environment. Because natural capital is absent from conventional economic frameworks and production functions and has only fairly recently become the focus of rigorous measurement efforts, this transition was largely unobserved: in the case of the missing productivity growth, natural capital was the dog that didn't bark.

If declining natural capital is a major factor underlying widespread declines in productivity growth, why did labour productivity declines become apparent later in emerging and developing economies than in advanced economies? Later industrialization may well have acted to defer declines in natural capital in developing economies – although this is hypothetical as only thirty years of natural capital data is available. Further, as labour productivity growth in these economies has generally been higher than in advanced economies over the past three decades, it may have been sufficiently robust to at least temporarily outweigh the negative impacts of natural capital decline. Country estimates of natural capital indicate that, because human and produced capital per capita are lower in developing countries, the relative weight of natural capital in total capital is higher (UNEP, 2023; World Bank, 2021). Because developing countries' economies are more heavily reliant on natural capital, their productivity growth going forward may be more acutely affected by natural capital declines.

Measured Declines in Natural Capital

Concerted attempts to measure natural capital have been undertaken over the past dozen years by both the United Nations Environment Program (UNEP) and the World Bank, due to growing recognition of its relevance to economic outcomes.[12] These measures initially included only the value of stocks of marketable resources such as timber and mineral reserves, but their scope has progressively expanded. As both sets of global measures are based on aggregations of national data, neither includes values for natural systems and assets outside national boundaries, such as the atmosphere or open oceans. Other ecosystems are also still outside the scope of both sets of measurements, which remain under development with respect to both data and methodology.

Since 2012, UNEP has produced four iterations of its Inclusive Wealth Index (IWI), which provides global measures of natural capital, human capital, produced capital and aggregated total capital, referred to as Inclusive Wealth (IW). These are based on the UN System of Environmental-Economic Accounting (SEEA), which integrates environmental and economic measures into a single framework. The most recent edition of the index assesses these capital measures for 163 countries covering 98 per cent of global population from 1992-2019 and also produces aggregate global measures (UNEP, 2023). Natural capital is defined to include: 1) three renewable resources (fisheries, forests and agricultural land); 2) 14 nonrenewable resources (three fossil fuels and eleven minerals); and 3) market and non-market values for some ecosystems.[13]

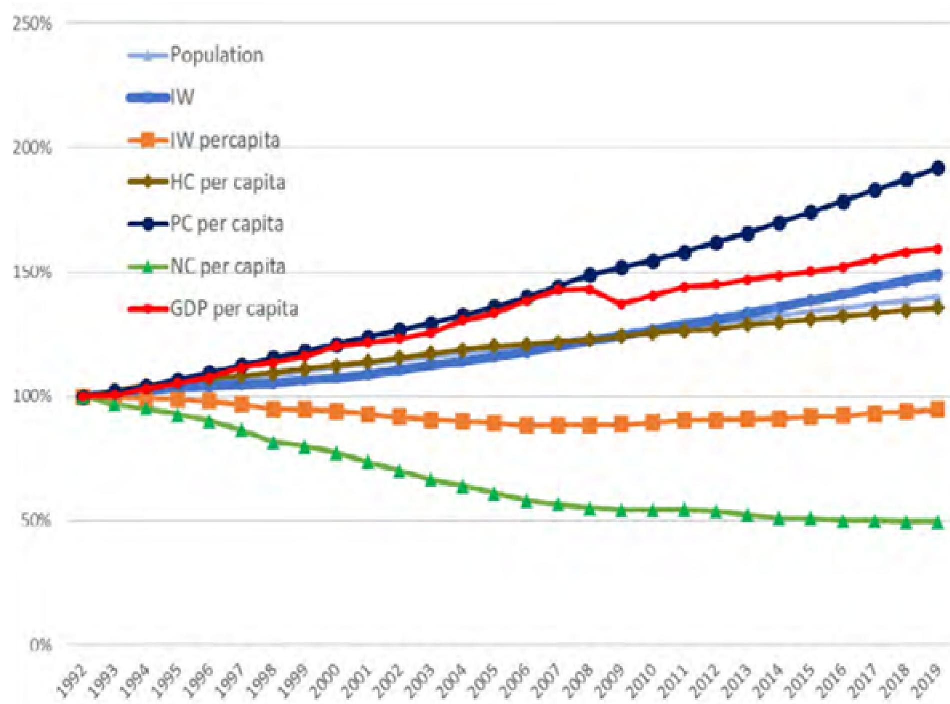
The value of natural assets is defined by the UNEP as the present discounted value of the future net benefits that can be expected over the life of the resource, based on a discount rate of 5 per cent. Thus the assessed value of forests, for example, goes well beyond timber values and also includes the value of: non-timber forest products; water filtration and regulation; soil stabilization; air filtration; erosion prevention; nutrient recycling; pollination; biodiversity protection; supplying wildlife habitat; providing a pool of genetic resources; moderating impacts of extreme weather events; and recreational uses. It also includes the value of sequestered carbon, assessed at the amount of sequestered carbon times the social cost of carbon, or the marginal net present social and economic cost resulting from an additional tonne of carbon dioxide emissions. Clearly, the assessed value of ecosystem services is highly sensitive to the values assigned to these parameters; it will rise if the estimated social cost of carbon goes up or if a lower discount rate is

12 Another motivating factor was the desire to develop measures other than GDP as indicators of well-being, i.e. to move "beyond GDP", based on recognition that measures of assets – a stock – are a useful complement to measures of annual output – a flow, and essentially a measure of 'throughput'.

13 Renewable resources, including ecosystem services, account for approximately 76 per cent of total natural capital in the most recent UNEP framework, with nonrenewables accounting for 24 per cent.

14 Estimates of the social cost of carbon have risen significantly in recent years, as the economic costs of climate change have become more apparent, and as lower discount rates have more frequently been incorporated into

Chart 7: Trends in UNEP Measures of Total Global Capital per Capita, by Asset Class, and Other Indicators, 1992-2019 (1992=100)



Source: UNEP (2023)

used. [14]

The UNEP findings are striking. Chart 7 shows that while produced capital (PC) per person grew by 92 per cent between 1992 and 2019 and human capital (HC) per capita by 38 per cent, global natural capital (NC) per capita declined by 50 per cent. The steep drop in natural capital per capita reflected both a 28 per cent decrease in total natural capital, and global population growth of 41 per cent over this period. Declines occurred for both renewable and non-renewable forms of natural capital, with renewables declining slightly faster. Natural capital per capita fell in 151 of the 163 countries analyzed.

The worldwide decline in natural capital was sufficiently large to depress the value of total global capital per capita, referred to by the UN as Inclusive Wealth (IW). By 2019, total global capital per capita, or IW, was 5 per cent below its 1992 value. Total capital per capita declined in over one quarter of the countries assessed.

Any decline in productive capital generally reduces productive capacity and hence productivity. A 50 per cent per capita decline in natural capital would therefore be expected to have a significant negative impact on labour productivity growth.[15] Be-

these calculations (Tol, 2023).

15 In fact, the UNEP acknowledges that its current measure of natural capital likely considerably underestimates the depreciation of natural capital, as it does not yet include many ecosystem and other environmental losses (UNEP, 2023).

cause the decline in natural capital was sufficiently large to reduce the world's total stock of productive capital per capita, the productivity impact should be even more pronounced.[16]

The UNEP found that in 15 of the countries that experienced declines in total capital per capita because of natural capital deterioration, TFP increases were not sufficient to compensate for the declines; all 15 of these countries were located in Africa and South America.

A further striking finding shown in the Chart is the divergence between global growth of GDP per capita and produced capital per capita. GDP per capita growth no longer keeps pace with growth of produced capital per capita; growth rates of produced capital per capita rose over the course of this period, while growth of GDP per capita slowed. The clear implication is that the productivity returns to investments in produced capital have declined over time.

The World Bank has also developed a series of world wealth accounts based on the UN SEEA, the most recent of which covers 151 countries between 1995 and 2020 (World Bank, 2024). Its measures of natural capital account for a smaller share of total capital than those of the UNEP – 8 per cent of total capital in 2020, compared with 18 per cent in 2019 in the UNEP measure – and explicitly treat renewable and nonrenewable natural capital as separate asset classes.[17] Renewable natural capital (6 per cent of total capital in 2020) includes: agricultural land, forests (timber; non-wood forest products and ecosystem services including recreation, fishing and hunting and water ecosystem services), hydropower, mangroves, and marine capture fish stocks. Non-renewable natural capital (2 per cent of total capital in 2020) includes fossil fuels (oil, natural gas and coal) and thirteen metals and minerals. The Bank uses a discount rate of 4 per cent in its calculations of net present value.

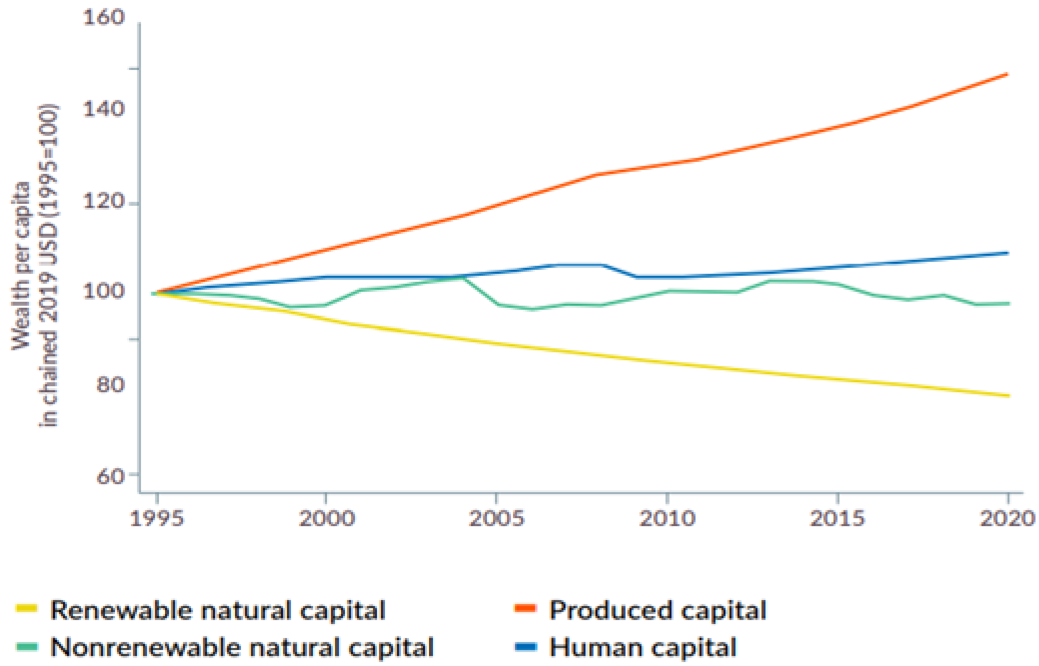
The World Bank, like the UNEP, finds significant declines in global natural capital per capita over the assessed time period. Chart 8 shows the World Bank assessments that between 1995 and 2020 on a per capita basis: global produced capital rose by 47 per cent; human capital rose by 9 per cent; nonrenewable natural capital declined by 2.5 per cent; and renewable natural capital declined by over 20 per cent.[18] However, while the UNEP declines in natural capital per capita were driven by both absolute declines in the value of natural capital and population growth, the World Bank declines were driven entirely by population growth, with a 5 per cent

16 The extent to which natural capital declines reduce the total quantity of capital depends on the relative shares of the three types of capital, which change over time. In 2019, those relative global shares in the UNEP framework were: human capital – 54 per cent; produced capital – 28 per cent; natural capital – 18 per cent.

17 The Bank's asset shares for human capital and produced capital are, accordingly, larger than those of the UNEP: human capital accounts for 60 per cent of total wealth in 2020 and produced capital for 32 per cent , compared with 54 per cent and 28 per cent , respectively for the UNEP in 2019.

18 In nonrenewables, a small increase in oil wealth per capita was offset by per capita declines in coal, natural gas, and minerals. In renewables, seven of the eight asset classes showed per capita declines; the value of marine fish stocks showed the steepest decline, while only per capita hydropower rose in value.

Chart 8: Trends in World Bank Measures of Global Capital per Capita, by Asset Category, 1995–2020



Source: World Bank (2024)

increase in measured natural capital globally over the 1995-2020 period. The Bank notes that both the share of natural capital and its per capita decline are likely underestimates, due to data and conceptual constraints on its ability to comprehensively measure renewable natural capital and ecosystem assets.

In addition the Bank, unlike the UNEP, found that total real per capita global wealth rose over the assessed period, by 21 per cent. This difference can be attributed to both the Bank's smaller measured natural capital share in total capital, and its lower per capita decline, compared with the UNEP. This is an important distinction as both the World Bank and the UNEP note, consistent with the economic consensus, that a minimum requirement for sustainable development is that total real wealth per capita does not decline – a state referred to as 'weak sustainability'. Declines in total per capita wealth are unsustainable as they signify erosion of the productive base and thus diminished future opportunities.

The Bank found that two thirds of the countries it assessed experienced growth in total per capita wealth, due to increases in human and produced capital; while 27 countries experienced declines or little change, many of these in sub-Saharan Africa.

The declines in measured global natural capital in both the UNEP and World Bank wealth measures are highly significant, as they represent growing production constraints in the global economy.

Impacts of Declining Natural Capital on Productivity

The impacts of natural capital declines on productivity growth can be mediated by one or more of the following transmission channels:

- GDP. A GDP decline, where physical capital and human capital remain constant, will produce a same-year drop in MFP growth, lowering the baseline for subsequent growth, with potentially compounding effects. A climate-related GDP decline could occur, for example, due to suspension of business activity because of wildfire smoke or inclement weather.
- Labour intensity and input. Adverse events such as extreme heat or wildfire smoke can directly reduce labour productivity via their impact on work effectiveness and/or hours per worker.
- Physical capital. Damage and destruction of physical capital reduce capital intensity and accelerate depreciation; they can also affect MFP by inducing capital / labour mismatch.
- Human capital. Illness, disability and premature mortality – due to, for example, air pollution – reduce lifetime worker output and also the return on investments in skills and education.
- Obsolescence. Unanticipated environmental changes can result in accelerated obsolescence, reducing the productive lifespan of investments.
- Dynamic impacts. Natural capital declines can affect productivity through their impact on variables such as business viability, investment, asset valuations, insurability, conflict and migration. Where feedback loops exist in the natural environment, natural capital declines can translate into further natural capital declines, with potential second order impacts.
- Reallocation effects. Declining natural capital can cause changes in the relative productivity of firms or industries, resulting in sectoral reallocation effects (Pilat, 2024).

Some of these productivity effects are immediate, or contemporaneous, while others are persistent. When negative output shocks are persistent or repeated, there is a cumulative and compounding impact on productivity growth. Similarly, where physical or human capital are damaged or diminished, the decline in productive capacity can result in ongoing as well as immediate impacts. Time lags in rebuilding physical capital mean that output losses can persist over a period of years, and rebuilding also diverts scarce resources that could otherwise be channeled into new productive capacity.

Insights from the Literature

The Economics of Biodiversity: The Dasgupta Review provides a broad framework for assessing interactions between the economy and nature (Dasgupta, 2021). In this and other publications, Dasgupta draws a clear distinction between two broad categories of natural capital: material contributions of nature, or provisioning goods, that are regularly included in measures of economic production; and environmental maintenance and regulating services, often referred to as ecosystem services, that create provisioning goods. He observes that expanded demand for provisioning goods has often directly diminished nature's ability to supply environmental maintenance and regulating services (Dasgupta, 2023).

Dasgupta notes further that the long-standing debate over the degree to which labour and produced capital can substitute for natural resources in production refers to provisioning goods, not maintaining and regulating services (Dasgupta, 2023). While there is some limited substitutability between provisioning goods and produced and human capital, there are no known substitutes for most environmental maintenance and regulating services. Indeed, these services are highly complementary to each other, such that damaging one can result in damage to others.

Other key characteristics of maintenance and regulating services that distinguish them from provisioning resources and from produced capital are:

- **Non-linearity.** Ecosystems can sustain incremental damage over an extended period and then suddenly collapse abruptly.
- **Irreversibility.** Depreciation of ecosystems is often irreversible within meaningful time periods.
- **Non-replication.** It is not possible to replicate a depleted or degraded ecosystem (Dasgupta, 2023).

Dasgupta articulates a view referred to as 'strong sustainability', which argues that because of limited substitutability of produced capital and human capital for natural capital, sustainable growth requires that each class of capital must be maintained; with poor substitution, growth is ultimately constrained by the most scarce factor of production.

Indeed, it is increasingly argued that natural capital and human capital are complementary rather than substitutes. Damania *et al.* (2023) for example, found that natural capital erosion can result in impaired human capital development, based on a study of the impacts of deforestation in 46 countries on health outcomes for 0.7 million children. They concluded that deforestation upstream affects water quality downstream, raising the incidence of diarrheal disease, nutritional deficiencies and childhood stunting, thereby affecting human capital development, with subsequent productivity impacts.

Gardes-Landolfini *et al.*, (2024) have developed an interesting conceptual framework for analyzing nature-related risks that incorporates many of these considerations and includes natural capital and social capital as well as human and produced capital, linking these to economic flows, sustainability paths, nature-related risks, financial risks and macroeconomic transmission channels including to productivity. The framework could serve as a useful basis for further development of approaches to integrating natural capital into economic analysis.

At a more granular level, considerable developmental work has been undertaken to integrate natural capital into productivity measurements. Using a conventional growth accounting approach in which output growth is viewed as a function of produced capital (PK), labour (L) and technology, changes in productivity growth can be disaggregated into the weighted effects of: changing capital intensity; changing labour composition; and a residual, multifactor productivity (MFP), that incorporates the portion of growth that cannot be directly attributed to either of the other variables. Accordingly, MFP is typically interpreted as an indicator of innovation and technological change as well as any mismeasurement of factors of production, but it can also reflect reallocation of inputs and organizational changes. Natural capital (NK) has not traditionally been included in this approach, which can be expressed as:

GDP growth = PK contribution + L contribution + MFP

It is generally acknowledged that natural capital can impact productivity growth either positively or negatively, under different sets of conditions, and that these impacts are often apparent within multifactor productivity, as it captures residual effects not measured elsewhere. There is no consensus, however, on the magnitude of these impacts, which depend on the assessed value of natural capital – itself determined by the methodology and scope of measurement used – or even on their direction.

However, a number of authors agree that failing to account for natural capital will tend to lead to an underestimation of 'true' MFP growth where natural capital stocks or use are declining, and to an overestimation where natural capital stocks or use are growing (e.g. Brandt *et al.*, 2013; Oleweiler, 2002). Because MFP is widely understood as largely reflecting technological change, this can be interpreted as meaning that the absence of natural capital in production functions can effectively inflate or deflate the presumed role of technological change, attributing: a greater than warranted share of credit for productivity growth to technological change when natural capital is growing; and a greater than warranted share of blame to weak technological change for productivity declines or stagnation when natural capital is declining. This is consistent with the interpretation set out in this article. Many commentators have therefore recommended that natural capital be accounted for separately as a factor of production.

Obst (2024) has set out entry points, or frameworks, that have been used to integrate natural capital and environmental impacts into productivity analysis, expressed in terms of gross value added (GVA). The main such frameworks used to date include adjustments for three variables:

- Natural capital, which can be included with produced capital and labour as a production input (i.e. GVA = PK + L + NK + MFP).
- Pollution and other negative environmental outputs, as negative adjustments to output (i.e. GVA – pollution = PK + L + MFP);[19]
- Expenditures to improve environmental outcomes, as positive adjustments to output: (i.e. GVA + environmental expenditures = PK + L + MFP);

The OECD has undertaken work to develop environmentally-adjusted measures of multifactor productivity (EAMFP) that incorporate two of these variables by ac-

19 Pollution could, in principle, alternatively be used to adjust natural capital measures.

counting separately for natural capital as a factor of production and also adjusting GDP growth to reflect air pollution abatement, using the following growth accounting formula:

GDP growth – Pollution abatement adjustment = L contrib. + PK contrib. + NK contrib. + EAMFP

The second iteration of the EAMFP measures, released in 2023, covers 52 OECD and G20 countries from 1996 to 2018. While the first (2018) iteration included only non-renewable resources (fossil fuels, metals and minerals) in natural capital, the 2023 version expanded the measure to include some renewable resources (land, timber and fisheries) and some ecosystem services such as coastal and watershed protection (Rodriguez *et al.*, 2023).[20]

The OECD analysis notably finds that natural capital negatively affected national economic growth more often than it contributed positively from 1996-2018. It acted to depress economic growth in 30 of the 52 countries assessed, and contributed positively in only 20 (Rodriguez *et al.*, 2023). (Its contribution was zero in two countries.) This finding is consistent with the thesis advanced in this article. In contrast, the OECD found that labour and produced capital contributed positively to national economic growth in nearly every instance.[21] The analysis also found that positive contributions of natural capital to national economic growth were largest among countries that rely heavily on resource extraction, i.e. Saudi Arabia, Russia, Australia, Chile, China and Brazil.

Scientific Evidence on the Deterioration of Natural Capital

The scientific assessments underlying measurements of declining natural capital are extensive. While there have been a few areas of improvement (e.g. the reversal of ozone depletion), they show broad and significant declines in key areas: a) climate change; b) biodiversity loss; c) soil and subsoil resource depletion; and d) waste, pollution and contamination.

Climate Change

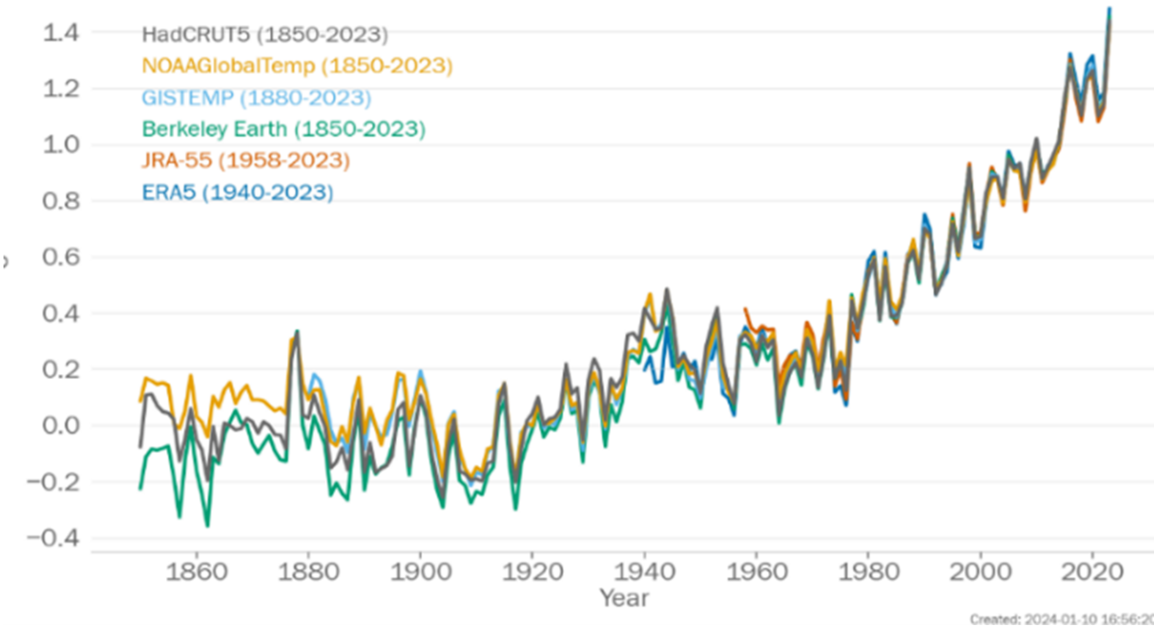
Atmospheric concentrations of greenhouse gases have reached their highest levels in two million years, driving accelerating manifestations of climate change (IPCC, 2023). By 2023, global air temperatures had risen to nearly 1.5° C above pre-industrial levels – the preferred upper limit under the Paris Agreement, (Chart 9) – and ocean temperatures had also risen significantly, to record high levels (Copernicus, 2024).

Rising air and ocean temperatures have

20 The OECD acknowledges that this definition of natural capital still excludes many resources (e.g. freshwater, soil, sand) and many foundational ecosystem services (e.g. carbon storage, pollination, water and air purification, habitat protection). Accordingly, its natural capital measure remains an incomplete one that – like many measures to date – is heavily weighted towards direct harvesting of resources (‘provisioning services’) as opposed to regulating ecosystem services. In addition, the OECD’s pollution measure does not include water or soil pollution.

21 The contribution of produced capital to GDP growth was positive for all 52 countries, while the contribution of labour was positive for 46 out of 52 countries

Chart 9: Global Average Temperature Compared to 1850-1900 Average



Source: World Meteorological Organization (WMO) (2024), based on six international datasets

led to much more frequent and intense extreme weather events, resulting in escalating property damage (IPCC, 2023). The frequency and intensity of hot extremes have increased, as has the incidence and duration of droughts, contributing to desertification and a doubling in the frequency of extreme wildfire events over the past twenty years (IPCC, 2023; Jones *et al.*, 2024; UNEP, 2022b).

Marine heat waves have also doubled in frequency, resulting in ecosystem damage including mass mortality events (Copernicus, 2024). Melting polar ice has contributed to rising sea levels that raise flooding risks for coastal areas. The incidence of climate-related food-borne, water-borne and vector-borne diseases has risen, and human and animal diseases are emerging in new areas (IPCC, 2023).

Biodiversity Loss

The term biodiversity is a concept that refers to diversity and population abundance within species, between species and within ecosystems. All biodiversity loss exacts costs in terms of ecosystem functioning and fragility, and delivery of benefits to humans (Diaz, 2006). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) conducts global assessments of biodiversity and ecosystem services on behalf of 140 member states. Its landmark first assessment report concluded that biodiversity is declining faster than at any time in human history, due largely to habitat loss, pollution and climate change (IPBES, 2019). It found that human activity has significantly altered 75 per cent of global land area and 66 per cent of the ocean. One fifth of global forests have been lost since 1900. The great majority of ecosystems show rapid deterioration, declining overall by 47 per cent in size and condition compared to baselines.

The global biomass of wild mammals has fallen by 82 per cent since prehistory (IPBES, 2019). Wild mammals now comprise only 4 per cent of the total global biomass of mammals, with humans (32 per cent) and domestic livestock (62 per cent) comprising the other 96 per cent. The total biomass of fish has dropped by 50 per cent, and many local populations have been fished to near extinction.

Nearly half (48 per cent) of all living species are experiencing population declines (Finn *et al.*, 2023). There has been an average 73 per cent overall decline globally in monitored populations of mammals, birds, fish, reptiles and amphibians since 1970 (World Wildlife Fund, 2024).[22] Over one quarter of all species are now considered to be threatened with extinction, leading a number of scientists to postulate that Earth is currently entering its sixth mass extinction event (Ceballos *et al.*, 2017; Finn *et al.*, 2023; Goulson, 2019; Kolbert, 2015; Sanchez-Bayo and Wyckhuys, 2019).

Of 18 categories of contributions of nature to humans assessed by the IPBES, fourteen declined over the past fifty years (IPBES, 2019). While direct material contributions from nature (agriculture, fish, bioenergy and timber) rose, all ten regulating contributions relating to environmental processes declined, leading the IPBES to conclude that rising material contributions are often not sustainable.[23]

Soil and Sub-soil Resource Depletion

Soil. One third of global land area, particularly cropland, has degraded soil with reduced productivity, due largely to unsustainable agricultural practices (FAO, 2015). High rates of soil erosion on agricultural land exceed natural rates of soil formation, causing net annual losses.

Groundwater. Groundwater is heavily relied upon worldwide for consumption, irrigation and industrial use, but many aquifers are being depleted by withdrawals that exceed rates of replenishment. Since 1980, rapid water level declines have occurred in nearly half (48 per cent) of assessed aquifers providing 75 per cent of global withdrawals, and the rate of depletion doubled after 2000 (Doll *et al.*, 2014; Jasechko, 2024). Only 7 per cent of aquifers displayed rising levels.

Nonrenewable Resources. Between 1970 and 2023, annual global extraction of metals, minerals and fossil fuels more than quadrupled (Vienna University, 2024). While exploration is ongoing, the richest and most accessible sources are generally exploited first. Subsequently developed reserves are often more remote, of lower quality, or more difficult to access.

Waste, Pollution and Contamination

Waste, pollution and contamination result in depreciation of the natural capital assets of air, water and soil.

22 Population declines are assessed on the basis of 35,000 populations covering 5,495 species.

23 These ten regulating contributions are: habitat creation and maintenance; pollination; air quality regulation; climate regulation; regulation of ocean acidification; regulation of freshwater quantity and quality; regulation of coastal water quality; formation, protection and decontamination of soil; regulation of hazards and extreme events; and regulation of detrimental organisms and biological processes.

Waste. The tripling of total global materials extraction since 1970 has produced comparable increases in waste. In 2019, the global economy consumed 106 Gt of material, generating 30 Gt of solid and liquid waste and 47 Gt of GHG emissions (UNEP, 2024).[24]

Air pollution. Air pollution has worsened in many locations, particularly parts of Asia, with rising concentrations of substances known to be damaging to human health and escalating global population exposure, despite air quality improvements in some countries (Brauer *et al.*, 2024; Health Effects Institute 2020).

Water pollution. Water pollution has worsened significantly in many parts of the world, with direct impacts on the health of humans and wildlife (IPBES, 2020). Globally, 80 per cent of industrial and municipal wastewater is discharged untreated (Lin *et al.*, 2022), and 300 million tons of industrial waste is released annually (IPBES, 2019). Marine and ocean plastic pollution has increased tenfold since 1980, and plastic is a particularly persistent contaminant (UNEP, 2021).

Soil contamination. Soil contamination is caused by factors including industrial, mining and military activity, transportation and nuclear accidents, improper waste disposal, agricultural chemicals and floods. It affects large areas of land globally, reducing the available stock of arable land and negatively affecting crop yields (FAO, 2015).

Natural Capital and Productivity: the Evidence

There is a rapidly growing literature on the productivity impacts of natural capital depletion in four key areas: a) climate change; b) biodiversity loss; c) soil and subsoil resource depletion; and d) pollution.

Climate Change

Macroeconomic Effects

The macroeconomic impacts of climate change have been extensively modeled in recent years. Climate change acts as an adverse productivity shock (Breckenfelder *et al.*, 2023). It reduces: output from a given stock of capital and labour; the supply of labour and capital, via extreme weather events; and aggregate spending via its effect on real incomes, further contributing to output reductions.

The majority of modelling exercises to date have been forward-looking rather than retrospective. It is now well accepted that climate change will have negative economic and productivity impacts, even under relatively moderate warming scenarios. Until recently, most projections found the anticipated economic impacts of climate change to be relatively modest (e.g. Herrnstadt

24 91 per cent of global consumption was derived from harvesting and extraction, and the balance from recycling.

25 Modest projected economic impacts based on Integrated Assessment Models have been critiqued as likely underestimating the impacts of climate change for reasons including: modelling changes in average temperature and precipitation but not higher incidences of extreme weather; modelling local rather than global climate phenomena; unrealistic ceteris paribus parameters in a highly dynamic context; unduly high discount rates;

and Dinon, 2020; Lepore and Fernando, 2023; Network for Greening the Financial System, 2023).[25]

However, much larger prospective impacts are now being modelled, linked to more robust underlying assumptions. Given that material global warming has already occurred, it is implausible that warming to date has had no impact on economic growth, even if impacts are accelerating with incremental temperature increases.

Bilal and Kanzig (2024) modelled the national and global macroeconomic impacts over a ten-year period of a 1°C rise in global mean temperature that persisted for two years.[26] They found that it led to substantial and significant declines in labour productivity, TFP, capital stocks, investment, national incomes and global GDP; persistent reductions in GDP and productivity growth; and an accelerated rate of capital depreciation, consistent with damage from extreme weather events. Labour productivity and TFP levels both declined by 2 per cent on impact and 10 per cent within four years, with declines persistent over the ten years assessed. World GDP fell by 2 per cent on impact and by 12 per cent within six years. They note that productivity losses drive most of these economic damages, and highlight the combined adverse impact of lower productivity and faster depreciation on capital accumulation.

Bilal and Kanzig also conducted a retrospective analysis of the 1960-2019 period, comparing economic trajectories under actual climate change (nearly 1°C of warming) to those in a baseline steady-state climate. They found that slower global growth due to global warming reduced world GDP per capita by 15 per cent by 2019 compared to the counterfactual. The annual growth effects of climate change were initially moderate but accumulated over time, with significant effects accruing after 2000. Between 2000 and 2019 climate change caused successively larger reductions in the annual world output growth rate, reducing the baseline growth rate by one third by 2019 (Bilal and Kanzig, 2024). The authors posit that these effects were not previously identified in part because the incremental nature of climate change has resulted in its effects being obscured behind background economic variability.

Bilal and Kanzig ascribe the large magnitude of their assessed economic impacts, compared to other analyses, primarily to their inclusion of global rather than local temperature shocks in their model; the effects of global temperature shocks were six to seven times larger than those for local shocks. This is consistent with the geoscience literature that extreme wind and precipitation are outcomes of global rather than local temperature variations.

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not accounting adequately for climate risks including exponential change, irreversibility, feedback loops, tipping points; not accounting adequately for other risks such as climate-related biodiversity loss, migration, armed conflict or widespread crop failures; and applying a general equilibrium framework to a situation that inherently reflects disequilibrium. See, for example, Council of Economic Advisers (2022); Dasgupta and Levin (2023), Stern and Stiglitz (2023).

26 They based this work on a standard neoclassical growth model and a climate-economy dataset encompassing analysis of 173 countries over 120 years.

Kotz *et al.* (2024) also found substantial growth impacts in forward projections of climate change relative to a baseline, producing a world income reduction of 19 per cent within 26 years independent of future emission choices. These impacts were mediated by the effects of climate change on labour and agricultural productivity, health, flood damage and conflict.

Burke *et al.* (2015b) showed that a strong relationship has existed worldwide at the national level since 1960 between average national annual temperatures and economic productivity, with productivity declining markedly at temperatures above 13.6° C. The global annual average temperature has steadily risen above this level, averaging 13.7° C from 1850-1900, 13.9° C from 1900-1999, and reaching 15.0°C in 2023 (Copernicus, 2024).

Sawyer *et al.* (2022) found that climate change is already resulting in large and rising annual GDP losses in Canada, and that by 2025 these annual losses would amount to 1 per cent of GDP, effectively cutting projected annual GDP growth in half. The most important channels of impact were weather disasters, heat impacts on labour productivity, and premature death.

Extreme Weather Events

Weather events such as hurricanes, tornadoes, extreme rainfall, extreme heat and wildfires reduce productivity immediately via GDP losses, and over longer periods via damage to human health, destruction of physical capital, diversion of resources from other productive investments, compromised business viability, and higher costs for insurance, prevention and adaptation.

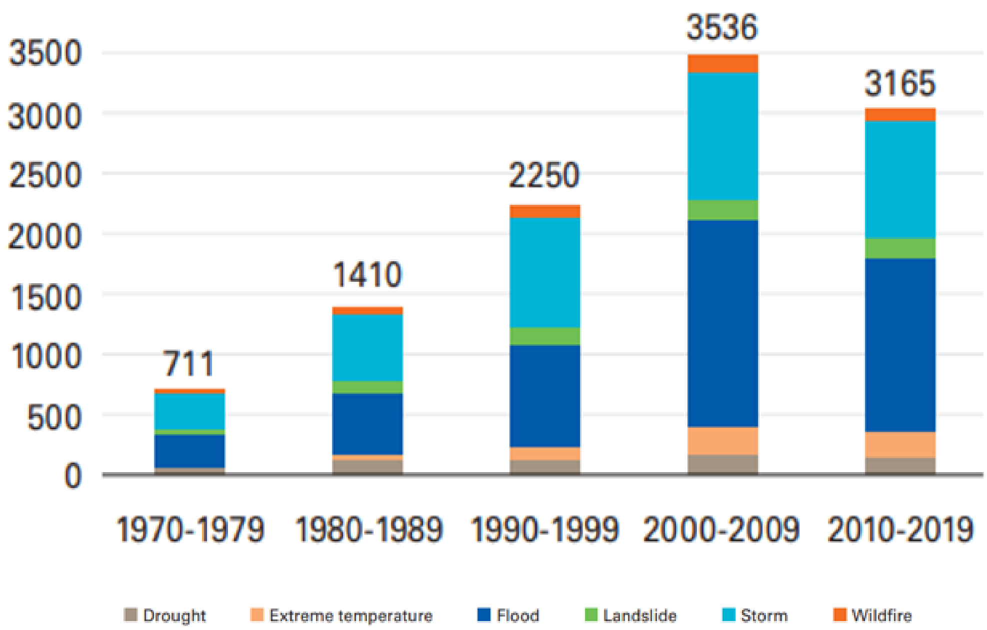
Such events – representing progressive loss of the ecosystem service of climate stability – are among the most costly forms of natural capital depletion in terms of output and productivity impacts, but are typically not included in Integrated Assessment Models (Newman and Noy, 2023).[27] Globally, they have increased in both frequency and severity, more than quadrupling from an average of 71 per year in the 1970s to an average of 335 per year since 2000 (Chart 10).

The real cost of these events has increased sharply as climate change has intensified. Property damage and destruction more than doubled in real terms from an average of $660 B ($2017 US) per decade from 1970-1989, to $1.4 trillion ($2017 US) per decade from 1990- 2019 (Chart 11). These costs, which represent only part of the total economic costs of extreme weather, were in the range of 0.2 per cent to 0.3 per cent of global GDP annually. Most such losses (62 per cent) are uninsured by private insurers and, in these instances, reconstruction and recovery can be slowed considerably by the need to secure refinancing to rebuild demonstrably risky assets (Swiss Re 2024).

Direct property damage costs associated with extreme weather can be very high relative to regional economic capacity, even

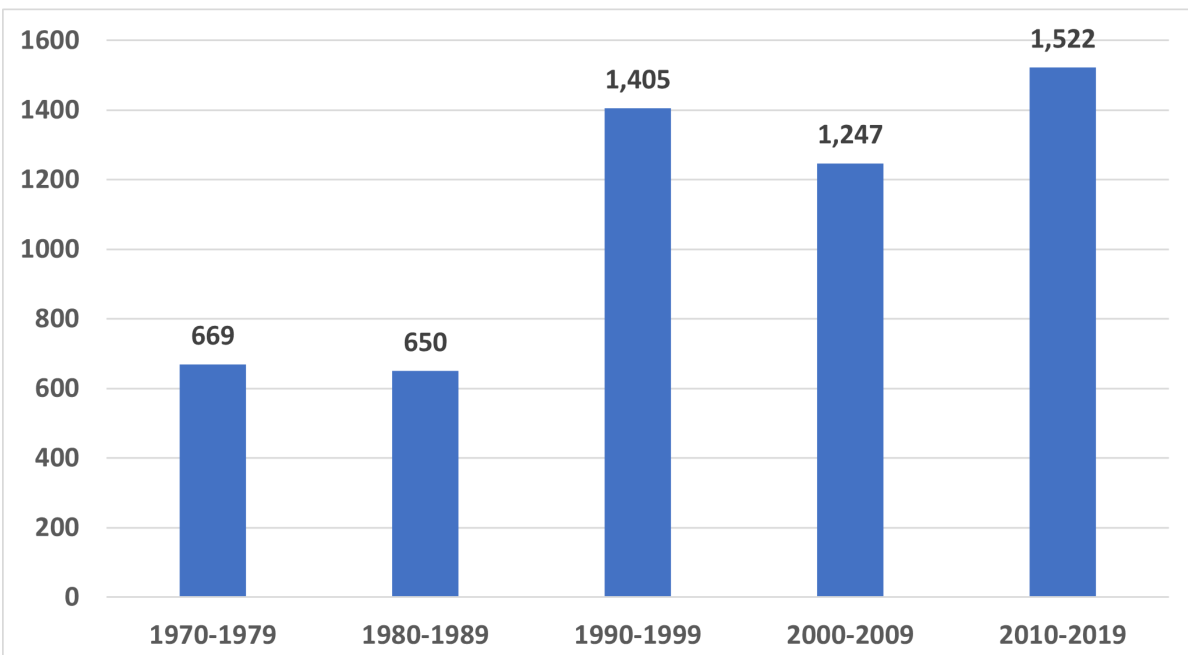
27 Integrated Assessment Models are models that incorporate both scientific and economic data in order to evaluate the nature and magnitude of environment-economy interactions.

Chart 10: Global Number of Reported Weather and Climate-Related Disasters, by Decade, 1970-2019



Source: WMO (2021)

Chart 11: Reported Global Economic Losses ($2017 US B) from Weather and Climate-related Disasters* (billions of 2017 USD)



These include droughts, extreme temperatures, floods, landslides, storms and wildfires. Source: WMO (2023), author's calculations exceeding regional GDP, as with 2017 hurricane damage in Puerto Rico (Anagnostakos, 2023). They often result in higher insurance rates and even insurance deserts where companies decline to extend coverage; indeed, the global cost of reinsuring properties against extreme weather has risen 2.4 times since 1992 (Smith, 2024). Lost output from business closures, evacuations and second-order losses are also often significant relative to regional and national capacity; the 2022 Pakistan floods were estimated to have reduced GDP by 2.2 per cent (Government of Pakistan *et al.*, 2022).

In addition to damaging physical capital and reducing GDP, extreme weather damages human capital via its impacts on injury, illness, mental health and mortality. The WMO found that 2.1 million deaths between 1970 and 2019 were attributable to the immediate impacts of weather disasters, corresponding to 190 deaths per event and 43,000 deaths per year (WMO, 2021). However, total mortality attributable to the longer-term health and economic effects of extreme events often greatly exceeds immediate, direct mortality. Young and Hsiang found that US tropical cyclones were consistently associated with robust increases in state-level excess mortality that persisted for 15 years, with each cyclone generating 7,000-11,000 excess deaths, compared with just 24 immediately reported deaths (Young and Hsiang, 2024).

A World Bank global analysis concluded that major adverse events, including extreme weather events, can inflict long-lasting harm on productivity via their impacts on human and physical capital, investment, innovation and global value chains (Dieppe *et al.*, 2021) .[28] Between 1960 and 2018, climate disasters reduced contemporaneous labour productivity in affected countries by an average of 0.5 per cent. The effects were persistent; after three years, severe climate disasters lowered national labour productivity by about 7 per cent in affected countries, primarily through weakened MFP. Because the frequency of climate disasters rose sharply over that period, the aggregate productivity impact of these disasters also rose over time. Country exposure to more frequent disasters was consistently correlated with lower national labour productivity and MFP growth.

Labour Productivity and Human Capital

It is well established that heat stress diminishes labour productivity. Labour productivity declines by 25 per cent at exposure to temperatures above 25° C; by 50 per cent above 33-34° C, and by 80 per cent above 35° C (Heal and Park, 2016; Kjellstrom *et al.*, 2019). Workers in outdoor occupations such as agriculture and construction are particularly affected. In 1995 approximately 1.4 per cent of total working hours were lost worldwide due to heat; that proportion has since risen, and is expected to reach 2.2 per cent by 2030 (Kjellstrom *et al.*, 2019). In 2023, heat exposure led to the the loss of 512 billion global work

28 Dieppe et al. analyzed 6,410 adverse events worldwide, including climate disasters, biological disasters, geophysical disasters, wars and financial crises.

hours – a 49 per cent increase above the 1990-1999 average – thereby reducing output per worker (Romanello, 2024).

Annual global heat-induced productivity losses have risen by 9 per cent over the past four decades (Parsons *et al.*, 2022). These losses comprised 2.6 per cent of global GDP in 2017, and more than 10 per cent of GDP in some countries. Globally, the increment in annual productivity losses attributed to rising temperatures was equal to 0.3 per cent of global GDP in 2017.

Heat-related mortality rates have been rising over time, with an annual average of 489,000 deaths globally ascribed to heat over the past decade (Zhao *et al.*, 2021).

Sectoral effects

A number of studies of have investigated the sectoral effects of climate change including in agriculture, mining and fossil fuels, hydroelectric power and manufacturing.

Climate change affects agricultural productivity via its impacts on both crop yields and labour productivity. Agriculture has consistently been found to be the sector most directly and adversely affected by climate change (e.g. Lepore and Fernando, 2023). While the sector accounts for only about 4 per cent of global GDP, it can have disproportionately large dynamic effects, as food scarcity is a well-established driver of migration and economic dislocation.

Global agricultural productivity and TFP grew strongly from 1960 through 2010 (Chart 12). However, growth in both slowed significantly after 2010 – a decline attributed to climate-related drought, heatwaves and floods (Fuglie *et al.*, 2024).

Climate change associated with a 1° C increase in global temperature was found to reduce global agricultural TFP growth between 1961 and 2020 by a cumulative total of 21 per cent; agriculture grew increasingly sensitive to climate change (Ortiz-Bobea *et al.*, 2021).

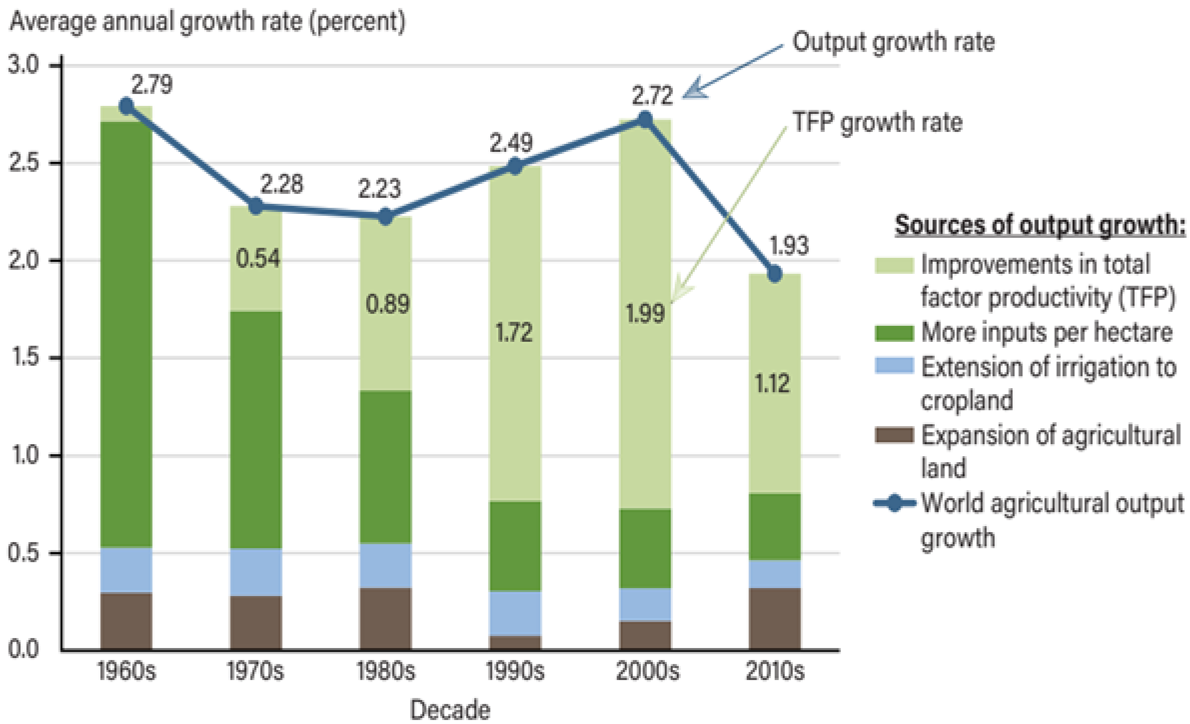
The Food and Agriculture Organization (FAO) found that disaster events reduced global agricultural GDP by growing amounts between 1972 and 2022, averaging 5 per cent over the entire period; this constituted an annual drag of 0.2 per cent of global GDP (FAO, 2023).

The effects of temperature on crop yield are highly significant. For every 1° C increase in global temperatures average global cereal yields decline by 3-10 per cent, implying cumulative global yield declines of 4.5 per cent - 15 per cent to date due to a nearly 1.5° C increase (FAO, 2024). Increasing heat has also raised the percentage of global agricultural working hours lost to heat stress, from 4.6 per cent in 1995 to 8 per cent by 2019 (Kjellstrom *et al.*, 2019).

Rising water scarcity and higher temperatures are both significant drivers of rising costs in the mining sector. A temperature increase of 1° C reduces mining productivity by 3 per cent, and extremely wet conditions reduce productivity by 1.5 per cent (Lepore and Fernando, 2023).

Hydroelectric power accounted for 13 per cent of global electricity generation in 2023. However, global hydro generation has declined since 2018 despite expanding capacity, primarily due to droughts and erratic rain that have caused numerous facilities worldwide to cut power levels or shut down altogether (Wiatros-Motyka, 2024). Over-

Chart 12: Sources of Growth in World Agricultural Output by Decade, 1961-2020



Source: Fuglie *et al.*, 2024

all, annual global power output relative to installed capacity has declined by 10 per cent since 2014 (IEA, 2024).

In China, a study of half a million manufacturing firms found MFP declines correlated with extremes of temperature, precipitation, humidity and wind speed (Zhang *et al.*, 2018). In India, labour productivity in manufacturing firms declined by 4-9 per cent on hot days, and national manufacturing output was estimated to have been reduced by at least 3 per cent by warming temperatures between 1971 and 2009 (Somanathan *et al.*, 2021). In Canada, Sawyer *et al.* found that by 2025 Canada's annual manufacturing production will have been reduced by 1 per cent due to the effects of climate change since 2015 (Sawyer *et al.*, 2022).

Dynamic Effects

Climate change affects productivity via a range of dynamic effects generally not included in Integrated Assessment Models including conflict, migration and natural capital feedback loops.

The risk of intergroup conflicts including wars has been found to be significantly heightened by climate change (Burke *et al.*, 2015a; Dieppe *et al.*, 2021). Dieppe *et al.* determined that armed conflicts produced the steepest productivity and TFP losses of all adverse events, with external wars reducing TFP by 10 per cent after three years and labour productivity by 12 per cent after three years.

Climate change is a recognized driver of mobility that can significantly raise rates of out-migration from affected regions, with productivity impacts in both source and destination areas (Burzynski *et al.*, 2022; Kaczan and Orgill-Meyer, 2019).

Feedback loops are well documented whereby natural capital losses set in motion changes that lead to further natural capital losses, with related productivity implications. In 2023, for example, higher global incidences of forest fires and drought due to planetary warming were shown to have significantly reduced the land carbon sink, impairing the ability of the natural environment to absorb human emissions and mitigate climate change (Ke *et al.*, 2024).

Impacts of Deterioration of Nature on Productivity

Deterioration of nature encompasses biodiversity loss, pollution, and other resource depletion. Governments and financial institutions are increasingly beginning to assess nature-related financial and economic risks (e.g. Asian Infrastructure Investment Bank, 2023; Network for Greening the Financial System, 2024; Swiss Re, 2020; Task Force on Nature-related Financial Disclosures, 2023; UNEP, 2021).

One such assessment was undertaken in the UK by the Green Finance Institute (GFI), based on risk scenarios including air and water pollution, soil health decline, pollinator decline and overexploitation of fisheries. The Institute concluded that each scenario would negatively affect economic growth, reducing UK GDP by 6-12 per cent within a decade (Ranger and Oliver *et al.*, 2024). It also concluded that incorporating nature-related risk into climate scenarios would double the estimated impact of climate change on the UK economy.

While the GFI scenarios are forward-looking, they have direct relevance to retroactive analyses. The types of natural capital losses included in the scenarios are not new but have been ongoing at significant scale for decades. It is therefore implausible that their economic impacts are just beginning now; it is much more likely that the impacts were not previously detected because we were not looking for them.

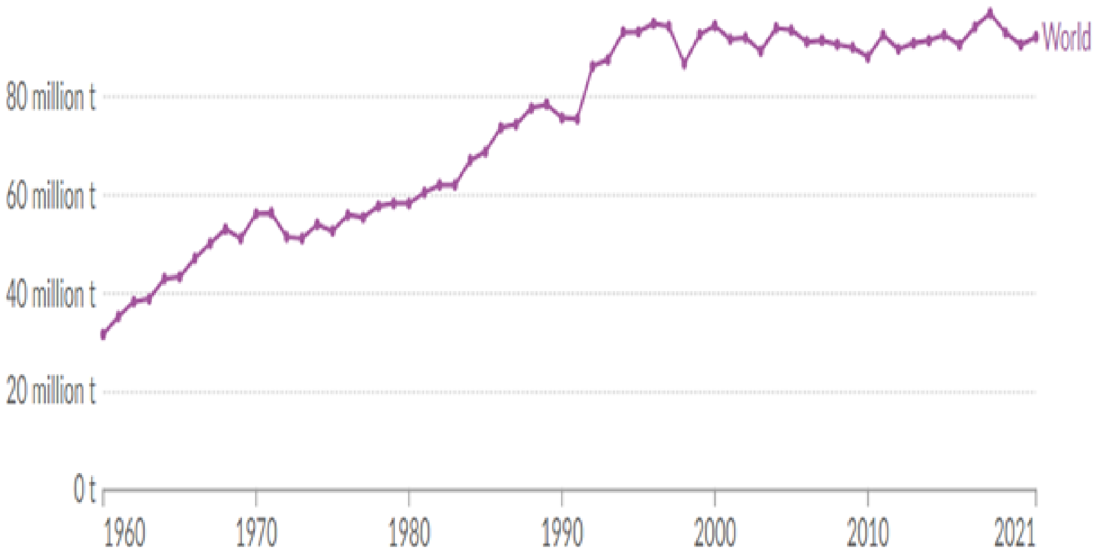
Depleted Fish Populations

In 2012, the value of global commercial capture fisheries was slightly under 1 per cent of global GDP (World Bank, 2012). Industrial fisheries have typically reduced local fish biomass by 80 per cent within 15 years, and by 2003 global large fish biomass was 90 per cent below preindustrial levels (Myers and Worm, 2003). Global wild fish catches peaked in the 1990s and have since stagnated (Chart 13).

The World Bank reported a 'tremendous' decrease in the productivity of global marine fisheries between 1972 and 2012, attributed largely to depleted fish stocks (World Bank, 2017). Technology advances and larger fleet size raised global fishing power at least fourfold, but fish catches rose by only 70 per cent, translating into a decline of 57 per cent in catch per unit of fishing power.

These global declines followed significant earlier regional declines. In the UK, Thurstan *et al.* documented rising fishery productivity – landings per unit of fishing power – from the 1920s through the 1950s (Thurstan *et al.*, 2010). Subsequently, however, catches declined steeply despite ongo-

Chart 13: Global Marine Wild Fish Catch, 1960-2021 (metric units tons)



Source: World Bank (2024) and Our World in Data

ing fleet investments, due to depletion of fish stocks. Fishery productivity dropped in tandem with fish populations, and by 2007 had fallen by 94 per cent from 1889 levels (Chart 14).

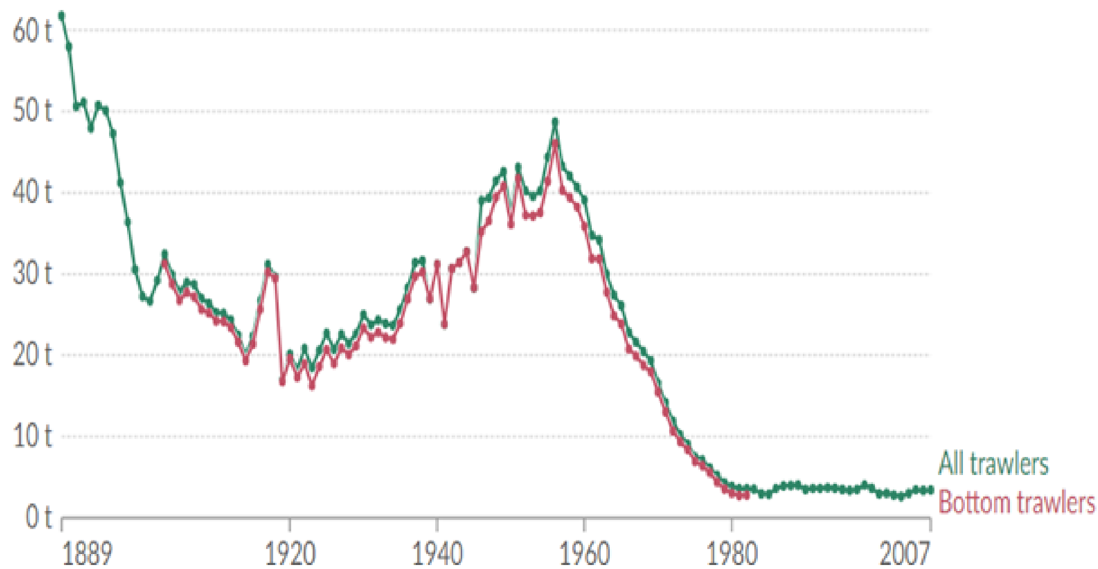
The asset value of global wild capture fisheries collapsed by 83 per cent between 1995 and 2018 due to depletion of fish stocks (World Bank, 2021). While farmed fish production has grown as marine catches have stagnated or fallen, it is an imperfect substitute. In addition to raising sustainability and health concerns, farmed fish are generally not available to the large numbers of people worldwide who rely on subsistence fishing as a primary food source (Pauly and Zeller, 2016).

Declining Wild Pollinator Populations

Pollination is necessary for the reproduction of three quarters of agricultural crops, representing 35 per cent of global crop volume; its value has been assessed at 1 per cent of global GDP (IPBES, 2016). However, large declines in wild pollinator populations have been documented worldwide; 53 per cent of butterfly and moth species, 46 per cent of bee species and 53 per cent of bird populations have declined in recent decades (Finn *et al.*, 2023; Sanchez-Bayo *et al.*, 2019).

Crop yield and quality depend on both the abundance and diversity of pollinators, and wild pollinators – the vast majority of pollinator species – have a stronger positive effect on crop yields than managed pollinators (IPBES, 2016; Reilly, 2020). Agricultural yields have been shown to be restricted when pollinator numbers were insufficient, and reduced when wild pollinator numbers or diversity have declined (IPBES, 2016, Reilly, 2020). Accordingly, as pollinator numbers have fallen, pollinator-dependent crops have experienced slower yield growth and lower yield

Chart 14: Productivity of the British Bottom Fishery, 1889- 2007 (Landings in tonnes per Unit of Fishing Power



Source: Thurstan *et al.* (2010)

stability than pollinator-independent crops (IPBES, 2016). Between 5-8 per cent of global crop production (valued at between US $235 - $577 billions in $ 2015) has been estimated to be at risk due to pollinator loss (IPBES, 2019). As wild pollinators have declined, agricultural producers have often been obliged to turn to alternate pollination methods such as managed hives and even hand pollination that are more costly and less productive than wild pollinators.

Declining Vertebrate Populations

Due to the high degree of interconnectivity in ecosystems, biodiversity declines have produced economic and productivity impacts, sometimes through unexpected channels. Bats provide significant agricultural services – valued in the United States at several billion dollars per year – by consuming insects that otherwise damage crops (Frank, 2024). However, some North American bat populations have dropped by 90 per cent since 2006 due to an emergent bat disease. In affected counties production costs rose as farmers compensated for the loss by increasing their use of insecticide, and average crop revenue per unit of land dropped by 29 per cent (Frank, 2024). Further, there was an 8 per cent increase in infant mortality following local declines in bat populations, which Frank attributes to the detrimental health impacts of higher environmental pesticide exposures.

In India, vultures long provided an important sanitation service through their scavenging activities. However, their population dropped precipitously after 1993 following increased use of a livestock drug that proved toxic to the birds. This population drop led to a 5 per cent rise in human mortality rates in affected districts, linked to both lower water quality and an increase in diseased feral dog populations

(Frank and Sudarshan, 2024). The higher mortality rates resulted in over 100,000 excess deaths per year nationwide, assessed at $69 billion per year in mortality damages.

Impacts of Depletion of Soil and Sub-Soil Resources on Productivity

Groundwater Depletion

Groundwater is heavily relied upon globally as a water source, including for agricultural production. Pumping improvements in the mid-20th century permitted agricultural expansion to dry areas where it would not otherwise have been possible (Hrozencik, 2023). However, high withdrawals exceeding replenishment rates have depleted many aquifers, particularly under irrigated cropland (Jasechko, 2024).

In India, groundwater supports 60 per cent of agricultural irrigation, but groundwater levels have dropped by an average of eight metres since the 1980s. These declines were found to be associated with significant yield reductions for winter crops of wheat, rice, sorghum and maize. Nationwide, each metre of decline in groundwater depth was associated with a 1 per cent-3 per cent decline in mean yields for these crops, implying that falling groundwater levels may have depressed the productivity of winter grain agriculture by 8-24 per cent over forty years (Bhattarai, 2021).

In the United States, over one third of agricultural acreage relies at least partly on groundwater irrigation, but over half of all US wells have had consistently falling water levels since 1940, reducing crop yields in some affected areas (Hrozencik, 2023). A 40 per cent decline in Kansas corn yields over twenty years was attributed to reduced groundwater availability, and the major aquifer underlying the state can no longer support industrial-scale agriculture (Rojanasakul *et al.*, 2023).

Aquifer depletion has also caused subsiding land levels and sinkholes, damaging buildings and infrastructure and increasing vulnerability to flooding (Jasechko, 2024). Globally, 6.3 million square kilometres of land inhabited by nearly 2 billion persons has been experiencing significant subsidence, and the rate of groundwater withdrawals has been found to be the most important predictor of the rate of subsidence (Davydzenka, 2024).

Soil Degradation, Erosion and Contamination

Soil degradation and erosion have significant negative impacts on crop yields; they can reduce yields by up to 50 per cent (FAO, 2021). Between 1945 and 2015, soil erosion resulted in a median annual decline of 0.3 per cent in global crop yields, or a 20 per cent cumulative global decline (FAO, 2015).

Soil contamination also negatively affects agricultural productivity by reducing crop yields (FAO, 2015). It affects large areas of land globally and therefore represents a significant constraint on agricultural production. In China, contamination of one fifth of all farmland by heavy metals is estimated to reduce national food production by 10 million tons per year (FAO, 2015).

Depletion of Mining and Oil and Gas Reserves

Ongoing exploitation of reserves typically depletes the highest quality and easiest to access sources first; production costs rise as more remote or lower quality reserves are accessed, lowering industry productivity. The Canadian experience provides an excellent example of this process. The multifactor productivity index for Canadian mining and oil and gas extraction industries declined by 62 per cent over six decades – from an index of 330 in 1961 to 126 in 2021 (2012 = 100) – as these industries shifted towards harder to access reserves (Statistics Canada, 2024b). Oil in particular transitioned from conventional sources towards costly and capital-intensive oil sands extraction that now accounts for two thirds of national oil production (Statistics Canada, 2024a). The decline was large enough to exert a significant drag on overall Canadian MFP growth. If MFP growth in mining and oil and gas had equalled that in the rest of the business sector from 1961 to 2021, cumulative growth in Canadian business sector MFP would have been 15 per cent higher (author's calculations).

Research on the impact of the oil sector on Canadian MFP growth between 2001 and 2018 concluded that the stagnation of Canadian MFP growth during this period can be entirely accounted for by higher oil production costs related to the shift towards oil sands (Loertscher and Pujolas, 2023).

Productivity Impacts: Pollution

Air pollution

Air pollution is known to produce a wide range of negative health impacts, reducing the stock of human capital via illness, disability and premature death (Brauer *et al.*, 2024; Health Effects Institute, 2020). Only one tenth of the world's population breathes clean air, while 90 per cent is exposed to pollution levels exceeding WHO guidelines (Health Effects Institute, 2020). Rates of global population exposure to hazardous levels of outdoor air pollution have risen significantly, and are highest in India, China, west Africa and eastern Europe (Brauer *et al.*, 2024; Health Effects Institute, 2022).[29]

An estimated 90 per cent of the economic costs of air pollution are related to its impacts on human health (OECD, 2016). Outdoor air pollution (particulate matter) was the leading contributor to the global disease burden in 2021 among 88 assessed risk factors, responsible for 120 million life years lost to illness or premature mortality, or 8 per cent of all life years lost (Brauer *et al.*, 2024).[30]

Illness and disability caused by air pollution reduce worker productivity by increasing absences from work, lowering average

29 The proportion of the global population exposed to hazardous levels of particulate matter rose by 43 per cent between 1990 and 2021, while exposure to hazardous levels of ozone rose by 45 per cent (Health Effects Institute, 2022).

30 This metric sums years of life lost due to premature death and years lived with disability.

output per worker. Outdoor air pollution in 2010 resulted in 1.24 billion lost workdays globally, 4.9 billion restricted activity days and 600 million partially restricted activity days – in aggregate, approximately 1 per cent of all global workdays (OECD, 2016). Outdoor air pollution was found to have negatively impacted labour productivity in all regions and in all sectors in 2016, slowing global economic growth by 0.1 percentage points in that year (OECD, 2016).

Premature deaths due to air pollution reduce the stock of human capital and the yield on investments in skills and education. Outdoor air pollution is the fourth leading global risk factor for early death and accounts for more than one in nine deaths worldwide, 4.4 million annually (Health Effects Institute, 2020).[31] Premature deaths from air pollution (indoor and outdoor) were estimated to have reduced global human capital by 0.3 per cent in 2018, at an estimated cost of $2.2 trillion ($US 2018), or 2.5 per cent of global GDP (World Bank, 2021). Human capital losses due to air pollution rose between 1985 and 2018.

Air pollution can directly lower labour productivity, even where it does not result in work absences. Among California agricultural workers, increases in ozone levels of 10 parts per billion (ppb) were found to be associated with 5 per cent reductions in worker productivity and decreases in hours worked (0.28 hours per day), translating into $700 million ($US 2012) in higher US agricultural labour costs per 10 additional ppb of ozone (Zivin and Neidell, 2012). Air pollution from US wildfire smoke was also shown to reduce quarterly per capita earnings in affected regions by .10 per cent for each day of smoke, reducing total US labour income by an average of 2 per cent per year over twelve years (Borgschulte *et al.*, 2022).

Air pollution has consistently been shown to adversely affect crop yield and crop quality, negatively affecting agricultural productivity (OECD, 2016). In China, ground-level ozone was found to reduce 2006 crop yields for wheat (10 per cent), rice (2.5 per cent), soybeans (2.2 per cent) and maize (0.3 per cent), reducing total national agricultural output by 1.1 per cent (Miao *et al.*, 2017).[32]

Overall, there is extensive evidence of pervasive worldwide natural capital declines exerting significant negative impacts on productivity in every major economic sector over an extended period of time. Because natural capital accounting is still in a developmental phase, these impacts have not yet been widely recognized. However, it is implausible that such significant and extensive negative impacts would not translate into reduced aggregate productivity growth.

31 Global death rates from outdoor air pollution rose by 39 per cent between 1990 and 2019, while those from indoor pollution fell by 65 per cent. Outdoor pollution now accounts for two thirds of all air pollution deaths. (World Bank, 2021).

32 Some previous studies found much higher crop losses attributable to ozone for rice (10-15 per cent), soybeans (16 per cent) and maize (22 per cent) (Miao *et al.*, 2017).

Summary and Conclusions

Environmental damage is eroding our economic prosperity. It has been slowing productivity growth for decades and may already have halted or even reversed it. As natural capital stocks have eroded, natural capital – which for centuries supported productivity growth – has become a limiting factor in the global economy. Consequently, its role shifted over the course of the 20th century from productivity accelerator to productivity decelerator.

Our collective natural capital deficit has diminished the global stock of productive capital, so that we have been building an ever-growing economic edifice on a dwindling natural capital foundation, at the risk of destabilizing the entire structure. Clearly, economic growth that erodes its own base is unsustainable.

The absence of natural capital from conventional economic frameworks has obscured these costs and artificially inflated conventional measures of productive capacity. A useful step in addressing the current misalignment between economic incentives and environmental sustainability would therefore be the systematic integration of natural capital into economic measurement, analytical and policy frameworks.

A key element of any productivity strategy should be reversing the long-term decline in natural capital by investing in its preservation and restoration. Because these issues are inherently global, the solutions must also be global in scope. Three key international frameworks are in place: the Paris Agreement on climate change; the Montreal-Kunming Biodiversity Framework, adopted in 2023 by nearly 200 nations; and the UN System of Environmental Economic Accounting, now in various stages of implementation in over 90 countries.

In addition, a new High Seas Treaty awaits ratification; and work has been underway to develop a Plastics Treaty, although these negotiations are currently stalled. It will be important to move with speed, ambition and creativity to adhere to the commitments in these international agreements, to advance them further, and to develop and implement appropriate policy tools and structures at the domestic and international levels. The energy transition towards carbon-free energy sources provides grounds for optimism by offering a potential basis for sustained and sustainable improvement in productivity and living standards.

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