Centre for the Study of Living Standards

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December 2025

THE DOG THAT DIDN'T BARK:

THE ROLE OF NATURAL CAPITAL IN EXPLAINING THE RISE AND FALL OF GLOBAL PRODUCTIVITY GROWTH

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ABSTRACT

This report examines the role of natural capital in economic and productivity growth. It proposes that natural capital should be considered a pivotal explanatory variable in the rise and subsequent decline of global productivity growth over the past five centuries, and presents extensive supporting evidence. Labour productivity and multifactor productivity (MFP) growth rates have been declining in advanced economies for several decades, with significant implications for living standards; 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 report presents an alternative explanation for the secular decline in global productivity growth: that erosion of natural capital has been occurring on a sufficiently large scale as 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 from the 16th century through the mid-20th century, to productivity decelerator subsequently. This role has been obscured due to the absence of natural capital from conventional economic frameworks and production functions.

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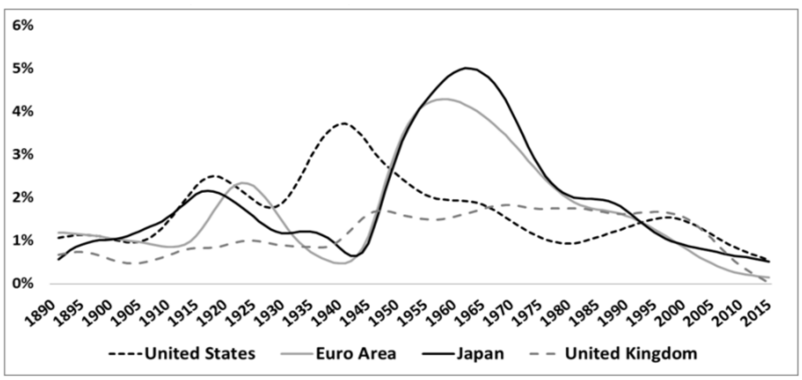
EXECUTIVE SUMMARY

This report examines the role of natural capital in economic and productivity growth. It proposes that natural capital should be considered as a pivotal variable in explaining the rise and subsequent decline of global productivity growth over the past five centuries, and presents extensive evidence in support of this hypothesis.

Productivity growth rates in advanced economies, particularly multifactor productivity (MFP) growth rates, have been declining for several decades, with significant implications for living standards (Chart 1). This decline has extended to emerging economies over the past fifteen years.

Chart 1. MFP trends in selected advanced economies, 1890-2015
Average annual growth rate



Source: Bergeaud et al. (2017b)

Despite extensive analysis and debate, no consensus has yet emerged on the reasons for the secular decline in labour productivity and MFP growth. However, the pervasive and persistent nature of the decline signals that factors of global scope and extended duration are likely implicated. One explanation that has achieved wide currency is that the most transformative innovations are now behind us (Gordon, 2012, 2013).

This report presents an alternative explanation for these ongoing declines in labour productivity and MFP growth: that environmental degradation, including progressive loss of climate stability – translated into economic terms as eroding natural capital – has become a significant driver of declining productivity growth in recent decades.

The foundation of all economies is natural capital, defined here in accordance 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, 2023c). Natural resources include all resources, living and abiotic, renewable and nonrenewable, such as soil, water, air, forests, plants, fish, wildlife, minerals and fossil fuels. Ecosystem services include processes such as oxygen generation, climate regulation, rainfall, pollination, carbon storage, flood protection, air and water filtration, waste decomposition, and provision of habitat for fisheries and wildlife.

Economists over most of the past century have treated production and productivity as a function of three factors: produced capital, labour or human capital, and technology. However, the fundamental role of nature in providing largely free services and goods – including clean water, fresh air, arable soil, habitat and a stable climate – was so taken for granted as essentially immutable that it was not accounted for in analytical frameworks or national accounts, or in the productivity analyses derived from them, but was instead generally treated as a "given".

Over the past half century, the demands of human economic activity on the natural environment have accelerated rapidly. Since the early 1970s global population has doubled, world GDP has quadrupled and global trade has grown tenfold (IPBES, 2019), while annual global material extraction from the natural environment has more than tripled (Vienna University, 2024).

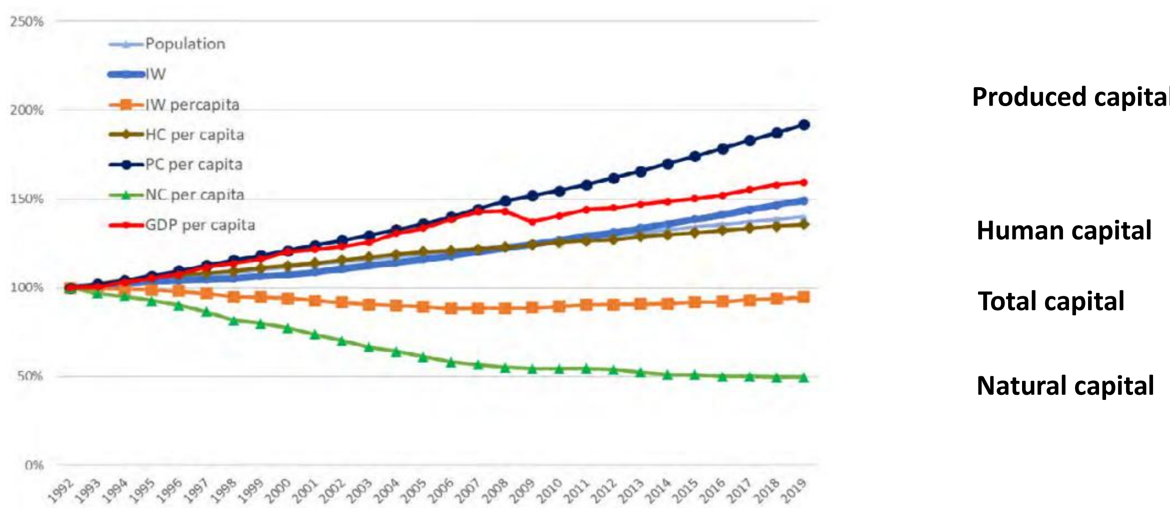
Human activities have resulted in significant depletion of natural resources and damage to ecosystems. These impacts have accelerated in recent decades, progressively outstripping the regenerative capacity of natural systems:

- Climate change has resulted in higher incidences of drought, heat extremes and other severe weather events, including hurricanes, cyclones, tornadoes and extreme rainfall (IPCC, 2023).
- Biodiversity has declined at an unprecedented rate, with an average drop of 73% in global populations of mammals, birds, fish, reptiles and amphibians since 1970 (WWF, 2024).
- The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has assessed eighteen categories of contributions of nature to humans. Fourteen of these eighteen categories have declined over the past fifty years, including nine out of ten key ecosystem services (IPBES, 2019).
- The rising annual extraction of material from the planet, 107 billion tonnes in 2024, has come with significant associated environmental impacts related to both its extraction and subsequent disposal, whether as production by-products, pollution or waste at the end of the consumption life-cycle. In 2019, the world economy generated 30 billion tonnes of solid and liquid waste, and 47 billion tonnes of greenhouse gas emissions (UNEP, 2024).

This environmental damage can be measured in economic terms as erosion of natural capital. Significant initiatives have been undertaken over the past dozen years to develop measures of the resources and ecosystem services that comprise natural capital. The natural capital measures developed by the United Nations Environment Program (UNEP) – the most comprehensive measures to date – show large declines, in alignment with scientific findings. Indeed, UNEP has found that global natural capital per capita declined by 50% between 1992 and 2019 – a drop considerable enough to more than offset gains in human and produced capital, reducing total productive global capital (Chart 2).

Any decline in productive capital normally reduces productive capacity and hence productivity. The UNEP findings are, accordingly, in alignment with the thesis of this report that erosion of natural capital has reached sufficient magnitude in recent decades to exert significant and growing downward pressure on productivity growth. As conventional economic frameworks and production functions do not include natural capital, this effect has been largely obscured: in the case of the missing productivity growth, natural capital is the dog that didn't bark.

Chart 2: Global changes in natural, human, produced and total capital (IW) per capita and other indicators, 1992-2019



Source: UNEP (2023)

A rapidly growing economic literature, surveyed in Section 7, provides substantial evidence of direct connections between damage to natural capital and significant negative impacts on productivity and output in a wide range of industries and locations. These productivity impacts can be immediate, but in many instances extend over a period of years.

Numerous transmission channels translate natural capital erosion into productivity declines:

- GDP decline;
- Reduced labour intensity or input;
- Damage or destruction of physical capital;
- Damage to human capital via illness, disability or premature mortality;
- Reduced human capital formation due to interrupted education or nutritional deficits;
- Accelerated obsolescence;
- Dynamic impacts on variables such as business viability, investment, conflict, migration, and the natural environment;
- Sectoral reallocation effects;
- Financial markets, via reduced asset values, lower supply of credit, higher insurance costs;
- Supply chains, which transmit shocks between sectors and geographic locations;
- Uncertainty, affecting willingness to invest.

***Climate change*.** Climate change acts as an adverse productivity shock, reducing the supply of capital and labour, the output from a given stock of capital and labour, and aggregate spending.

Researchers have found a strong inverse relationship between GDP per capita growth and both average national temperatures above 14°C, and rates of temperature increase (Burke, Hsiang and Miguel, 2015b; Burke and Tanutama, 2019). One analysis finds that cumulative global economic damage from climate change to date amounts to approximately $US 50 trillion in foregone income (Hsiang, 2025). Another study estimates that slower global growth due to climate change, largely attributed to lower productivity growth, reduced annual world GDP per capita by 15% between 1960 and 2019 (Bilal and Kanzig, 2024).

In Canada, climate change just since 2015 was found to be resulting in large and rising annual GDP losses, amounting to 1% of GDP by 2025. (Sawyer et al., 2022). While a 1°C temperature increase was associated with average reductions in real GDP growth of over 1 percentage point per year from 1965 - 2020 in emerging market economies, and approximately 1.5 percentage points per year in low-income economies (Amiot & Thompson, 2025).

Extreme weather events have increased sharply in frequency and severity in tandem with climate change. These reduce productivity in the short term via work interruptions, business closures, evacuations, death and injury, disruption of transportation and supply chains, and loss of utilities. Over the longer term, extreme weather affects productivity via damage and destruction of productive capital, including human capital, equipment, buildings and infrastructure. Reconstruction and repair are often lengthy, reducing output for the duration of the rebuilding period, and generating deadweight economic losses by diverting funds from other investments. When losses are uninsured – as in the majority of cases – rebuilding may not occur at all.

Significant and lasting damage to productivity and output has been widely documented as a result of extreme weather events. Globally, severe climate disasters were found to have lowered national labour productivity by an average of 7% after three years in affected countries, primarily through weakened MFP (Dieppe et al., 2021). Cyclones and hurricanes strongly reduce GDP growth, with the negative impact persisting for 15 years before partial recovery begins; full recovery to baseline does not occur by even the 20-year point (Hsiang & Jina, 2014). In the US, hurricanes are also associated with robust increases in state-level mortality that persist for 15 years (Young & Hsiang, 2024).

Climate change has more than doubled the frequency of extreme wildfire events over the past two decades. Wildfires now account for nearly half of annual forest loss and significant greenhouse gas (GHG) emissions, and net GHG absorption by global forests has therefore declined sharply (Harris & Rose, 2025; Jones et al., 2024; MacArthy et al., 2025). Increasingly prevalent wildfire smoke has recently reversed previous air quality improvements in Canada and the US (Greenstone et al., 2025). Globally, exposure to wildfire smoke is estimated to have caused 154,000 deaths in 2024 (Romanello *et al.*, 2025).

Rising heat stress due to climate change directly reduces labour productivity (Heal and Park, 2016; Kjellstrom et al., 2019). It also raises mortality rates, accounting for a global average of 546,000 annual deaths between 2012 and 2021(Romanello et al., 2025).

Global agricultural productivity and TFP growth have slowed significantly since 2010, to an average of only 1.1% per year between 2011 and 2020 -- a decline attributed to climate-related drought, heatwaves and floods (Fuglie et al., 2024). The decline has coincided with rising real global food prices, which had trended down throughout most of the 20th century (FAO, 2025).

Biodiversity and nature loss. Research provides evidence of significant economic losses resulting from biodiversity and nature loss:

- Overfishing on both sides of the North Atlantic has led to huge declines in fish catch and fishery productivity since the mid-20th century (Schijns et al., 2021; Thurstan et al., 2010).
- Globally, fish prices have tripled since 2000 as fish populations, catches and fishery productivity have all declined (FRED, 2025).
- Large declines in wild pollinator populations have been shown to have reduced agricultural yields and productivity (IPBES, 2016; Reilly, 2020).
- Deforestation has been directly linked to higher incidences of malaria, dengue fever, and diarrheal disease; and deforestation-induced rainfall loss in the Amazon has led to reduced hydropower production and lower agricultural productivity (Damania et al., 2025).
- A drop in India's vulture population resulted in a 5% rise in human mortality rates in affected districts, linked to both lower water quality and an increase in diseased feral dog populations, causing 100,000 excess deaths per year (Frank and Sudarshan, 2024).
- A causal link has been established between waves of amphibian population collapse since 1980 due to a fungal pathogen epidemic, and large and prolonged waves of increased human malaria incidence (Springborn et al., 2022).
- The 70% drop in the global whale population in the 20th century, due to large-scale whaling, proportionately reduced the significant carbon sequestration services provided by this population, previously amounting to 1.7 billion tons of CO2 annually (Chami et al., 2019).

Depletion of soil and sub-soil resources. Depletion of groundwater, soil, and mineral and fossil fuel reserves have had significant productivity impacts:

- Declining groundwater levels have been linked to reduced crop yields and agricultural productivity in India and the United States (Bhattarai, 2021; Rojanasakul et al., 2023). They have also caused significant land subsidence globally, including sinkholes, in land inhabited by nearly two billion persons, damaging buildings and infrastructure (Davydzenka, 2024).
- Between 1945 and 2015, soil erosion resulted in a median annual decline of 0.3% in global crop yields, or a 20% cumulative global decline (FAO, 2015).
- In Canada, a study concluded that the stagnation of national MFP growth between 2001 and 2018 can be entirely accounted for by higher production costs for oil related to the shift from conventional oil towards oil sands (Loertscher and Pujolas, 2023).

Pollution, waste and contamination. These factors affect productivity via their impacts on human health and mortality as well as by affecting the health of the natural environment, including food sources:

- Approximately 90% of the global population lives with degraded land, or polluted air, or unsafe water (Damania et al., 2025).
- Pollution was determined to be responsible for 9 million deaths in 2019, or one in six deaths worldwide (Fuller et al., 2022).
- Outdoor air pollution was the leading contributor to the global disease burden in 2021 among 88 risk factors, responsible for 8% of all life years lived with a disability or lost due to premature death (Brauer et al., 2024). It accounts for one in nine deaths worldwide, reducing global life expectancy by 1.9 years (Greenstone et al., 2025; Health Effects Institute, 2020). The economic damages associated with these health impacts have been assessed at $US 6 trillion per year, equal to 4.6% of global GDP (World Bank, 2025a).
- One quarter of the global population, over 2 billion people, drink water contaminated with feces, which is linked to diarrheal disease, cholera, dysentery and typhoid (World Bank, 2025; Damania et al., 2025).
- Unsafe drinking water, together with inadequate sanitation, is responsible for 1.4 million deaths globally each year (2.5% of all deaths) and 74 million disability-adjusted life-years (DALYs) lost, or 2.9% of all DALYs (Hay et al., 2025). It is a leading risk factor for death and disease among children under age five (Herrera et al., 2017).
- Plastics and persistent organic pollutants prevalent in the environment have been linked to a wide range of serious human health impacts, including cancer, cardiovascular disease and neurological damage (UNEP, 2023a, 2025).

A historical perspective

Economic historians have generally concluded that human living standards did not materially rise for many millennia. However, in the past few centuries this long stagnation came to an end. GDP per capita began to rise, initially in Western Europe and then elsewhere, slowly at first and then at an accelerating pace, resulting in unprecedented growth in output and income per person.

After such a long period of close to nonexistent growth, what changed? What factors provided the impetus for the growth acceleration that began around 1500? Theories of economic growth have primarily focused on the roles of physical capital, human capital, and innovation and technology. While these have all clearly been important, little attention has been paid to the role of natural capital – largely because both the concept and serious efforts to measure it are relatively recent. Theories of economic growth should be rethought to incorporate the significant explanatory power of natural capital. Indeed, a compelling case can be made that natural capital is a pivotal variable in the rise and subsequent fall of global productivity growth.

This report posits that from the early 16th century to the middle of the 20th century, growing access to natural capital supported rising productivity, but since that point natural capital depletion has become an increasing drag on productivity growth.

Over a period of some four centuries, beginning around 1500, growing exploitation of natural resources and the natural environment were key catalysts for rising productivity and the associated global growth take-off. Expanding travel and trade initially resulted in an enormous expansion of the de facto resource base, or natural capital, available to market economies for economic production, while also providing an escape valve from the growth constraints of localized resource depletion. Later, energy derived from fossil fuels fueled industrial and infrastructure growth and enabled the development of new technologies during the first and second Industrial Revolutions. During this period, resource depletion and environmental damage occurred, but generally remained within the regenerative capacity of Earth systems.

However, sometime after the middle of the 20th century, human economic activity began to progressively surpass the Earth's carrying capacity. That is, we collectively began to run a growing natural capital deficit, with net erosion of natural capital occurring as subtractions from natural capital exceeded regeneration by progressively larger amounts. Since that point, accumulated and accelerating damage to the natural capital foundation of all economies has increasingly slowed productivity growth and, accordingly, economic growth. Consequently, 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.

The timing of this inflection point is supported by scientific analyses that find that the impact of humans on the Earth system has accelerated since the mid-20th century (Steffen et al., 2015). Environmental footprint analysis finds that humans collectively began to exceed the ability of Earth to provide resources sustainably around 1970 (Wackernagel & Rees, 1995). The planetary boundary framework finds that nine planetary boundaries have been progressively breached, with seven of the nine transgressed by 2025 (Caesar et al., 2024; Findlay et al., 2025). And the impacts of climate change have become readily apparent only in the past fifty years.

Productivity growth, then, was maintained at a high level for an extended period of time in large part by reliance on fossil fuels, at the expense of clean air and a stable climate, and by the depletion of many resources that were not used sustainably. However, environmental damage is now eroding global economic prosperity. It has been slowing productivity growth for decades and may already have halted or even reversed it.

Conclusion

Natural capital is the foundational asset underpinning the global economy. Its absence from economic frameworks and its invisibility in economic indicators have obscured the real costs of its depletion, generated incentives for unsustainable misallocation of resources, and artificially inflated conventional measures of productive capacity. The consequence is that we have collectively been running a natural capital deficit for decades that has diminished the total stock of productive capital.

As natural capital stocks 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. An ever-growing economic edifice has been built on a dwindling natural capital foundation, at the risk of destabilizing the entire structure. Clearly, economic growth that erodes its own base is unsustainable.

A necessary step in addressing the current misalignment between economic incentives and environmental sustainability is therefore the systematic integration of natural capital into economic measurement, analytical and policy frameworks. Further, a key element of any productivity strategy should be investing in the preservation and restoration of natural capital.

THE DOG THAT DIDN'T BARK: THE ROLE OF NATURAL CAPITAL IN EXPLAINING THE RISE AND FALL OF GLOBAL PRODUCTIVITY GROWTH

1. Introduction[1]

This report examines the role of natural capital in economic and productivity growth. It argues that natural capital should be viewed as a pivotal explanatory variable in the rise and subsequent decline of global productivity growth over the past five centuries.

The case for this argument is set out in the balance of this report, as follows. Section 2 sets out the declining productivity performance of advanced and emerging economies over the past several decades. Section 3 examines the role of natural capital in economic and productivity growth in a historical perspective, including how that role changed in the latter half of the 20th century. Section 4 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 pollution and waste. Section 5 sets out the parallel declines in natural capital over time that are apparent in recent natural capital measurements. Section 6 looks at insights from the literature on natural capital. Section 7 examines the transmission channels from declining natural capital to productivity, and reviews the growing body of evidence on how deteriorating natural capital has translated into significant productivity declines worldwide, in the four areas examined in Section 4. Section 8 looks at the implications of these findings, examines some possible future directions, and offers some concluding thoughts.

2. The Secular Decline in Global Productivity Growth

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

Using a conventional production function in which labour productivity (output per person-hour) is viewed as a function of productive capital, labour and technology, changes in labour productivity can be disaggregated into the effects of: changing capital intensity; changing labour composition; and a residual, multifactor productivity (MFP), that incorporates that portion of productivity growth that cannot be directly attributed to changes in either capital intensity or labour composition. Accordingly, MFP is usually interpreted as an indicator of innovation and technological change, as well as any mismeasurement of factors of production – although it can also reflect reallocation of inputs, and organizational changes.

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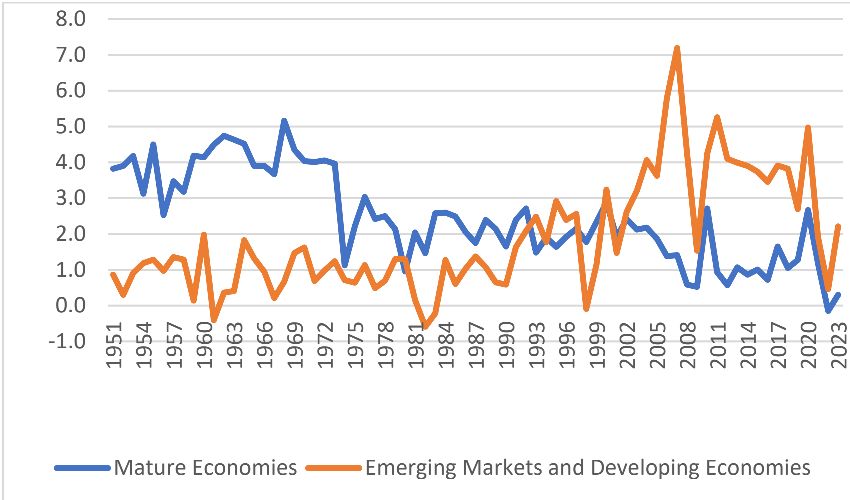
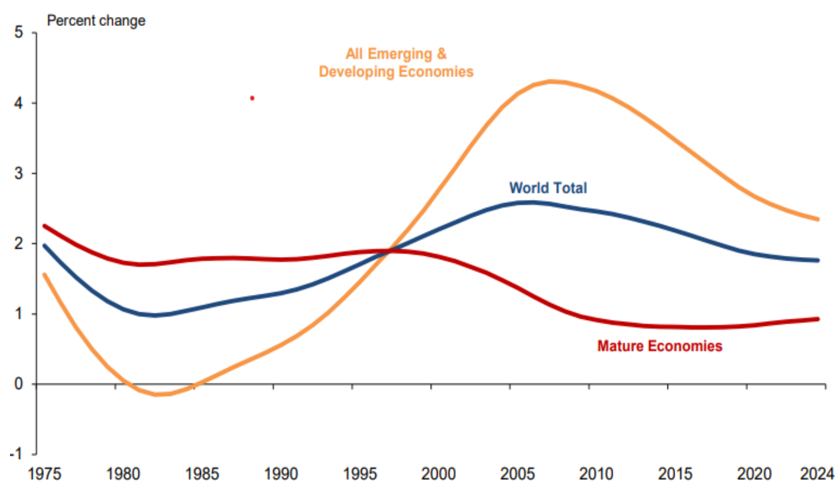
[1] Christina Caron's career as an economist and executive has included positions in the Canadian public service, the offices of two Canadian Prime Ministers and a federal Cabinet Minister, four think tanks and the British Embassy in Washington, D.C. An abridged version of this paper was published in December 2024 in the *International Productivity Monitor* (Caron, 2024) https://www.csls.ca/ipm/47/Caron_final.pdf. The author wishes to thank Andrew Sharpe and Glen Hodgson for constructive and insightful comments on both versions. E-mail: christinalcaron@gmail.com.

Chart 1: Annual growth in hourly labour productivity (%)
Mature and Emerging Market and Developing Economies, 1951-2023[2]



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

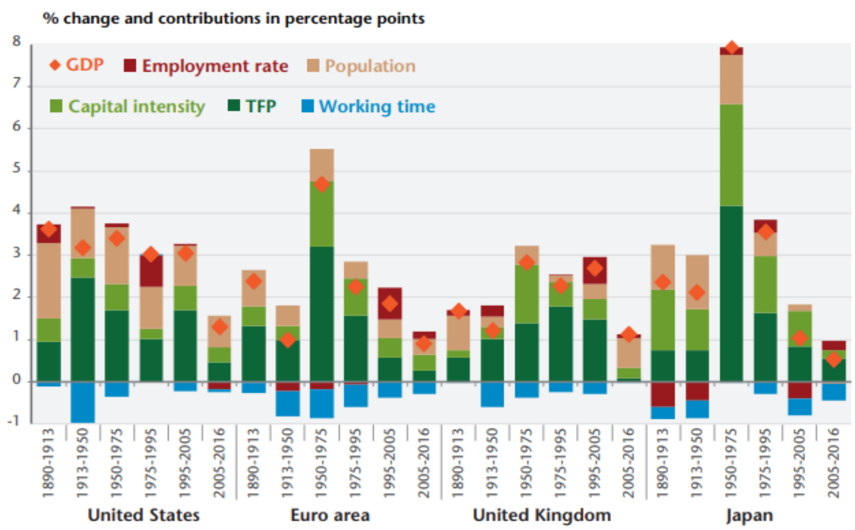


Note: Trend growth rates obtained using HP filter, assuming lambda=100
Source: The Conference Board (2024)

[2] 42 countries are currently considered to have advanced economies, with high per capita incomes and stable, diversified economies; this includes nations in the G7 and the Euro area, plus others such as Australia, Singapore and Korea. 96 countries, including Brazil, Russia, India, China and South Africa (BRICS) are classified as emerging market economies, characterized by middle income levels, sustained growth, stability, and production of higher value-added goods. 58 countries are classified as developing economies, with lower income levels and less diversified and stable economies (IMF, 2025).

Prior to the slowdown of the past several decades, multifactor productivity growth was the primary driver of productivity growth in most advanced economies (Chart 3) (Baily, 2023; Bergeaud *et al.*, 2016, 2017a, b, 2018; Easterly and Levine, 2001).[3]

Chart 3: Contributions of TFP and other drivers to average annual GDP growth, 1890-2016[4]



Source: Bergeaud, Cette and Lecat (2018)

However, since the beginning of this prolonged slowdown, much of the overall decline in productivity growth has been attributed to a pronounced slowing of multifactor productivity growth over the same period (Bergeaud *et al.*, 2017; Dieppe, 2021; Moss *et al.*, 2020). 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 technologies (ICT) revolution – the underlying trend has been downward.

Chart 4 shows that MFP has been trending down following a WWII boom in the United States and following post-WWII booms in Europe and Japan – since the 1950s for the Euro area, the 1960s for Japan and the 1980s for the UK. By 2015, growth rates had fallen in all four areas from peaks of between 2% and 5% annually to less than 1% annually.

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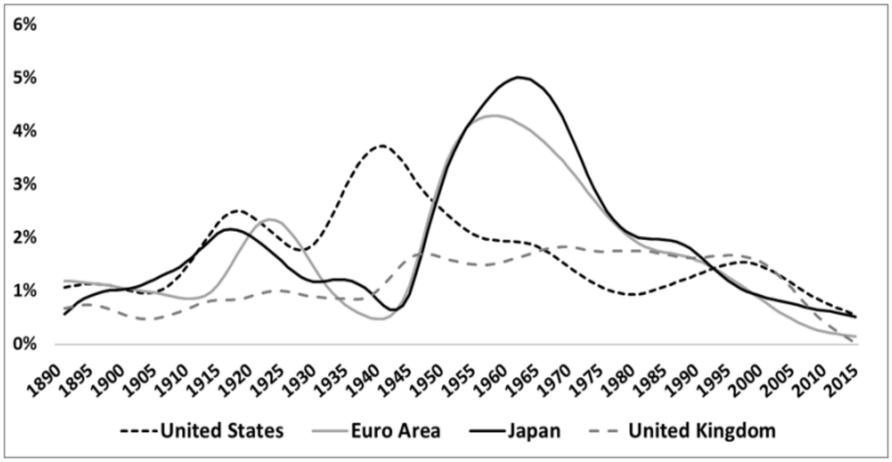
[3] Note that "productivity" refers throughout this paper to labour productivity. Multifactor productivity (MFP) is referred to as multifactor productivity or MFP – or, where appropriate in alignment with source references, as total factor productivity, or TFP.

[4] Note that in Chart 3 the percentage change in labour productivity is equal to the sum of the percentage changes in TFP and capital intensity.

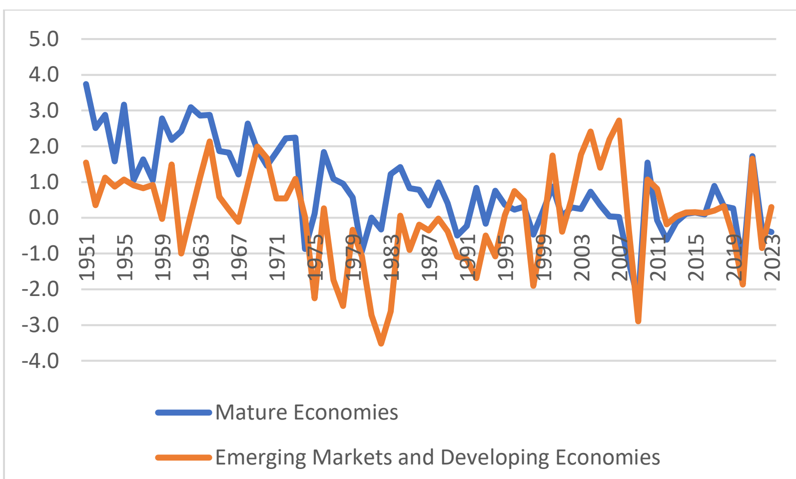
Chart 4: MFP trends over time in advanced economies, 1890-2015
Average annual growth rate



Source: Bergeaud, A., G. Cette and R. Lecat (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 (Chart 5).

Chart 5: Annual growth in Total Factor Productivity,
Mature and Emerging Market and Developing Economies, 1951-2023
(Change in natural log)

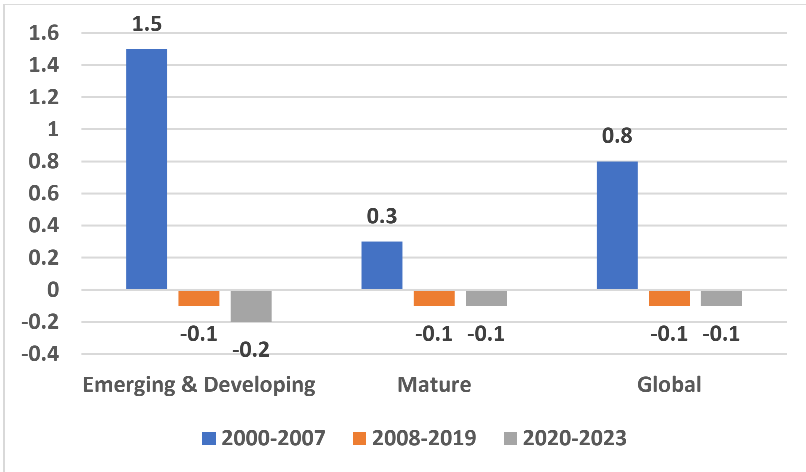


Source: The Conference Board Total Economy Database

Indeed, since 2007 global MFP growth has essentially flatlined, declining into slightly negative territory in both advanced and emerging economies (Chart 6) (The Conference Board, 2024).[5]

[5] The 2020-2023 period reflects, of course, the impact of Covid and the post-Covid recovery and cannot therefore be viewed as independent of cyclical influences.

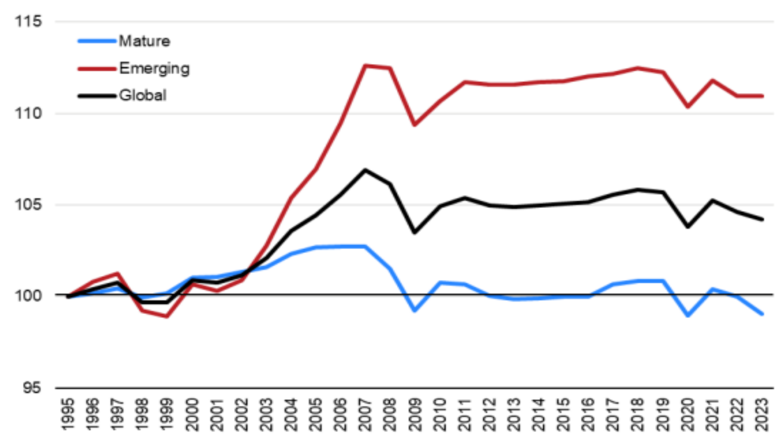
Chart 6: TFP growth, 2000-2023: Global, emerging and developing, and mature economies Average annual growth (%)



Source: The Conference Board Total Economy Database (2024)

Chart 7 shows that total factor productivity (TFP) peaked in 2007 for mature economies, emerging economies and also at the global level. The total factor productivity index has actually declined since 2007 both for mature economies and globally, and is essentially flat for emerging economies – although the 2023 level for these economies is slightly below the 2007 peak.

Chart 7: Total factor productivity level (index, 1995=100): Global, mature and emerging economies



Source: The Conference Board, 2024

These trends are of significant concern, as productivity growth is at the core of our prosperity and underpins any improvement in measured living standards – particularly at this juncture, when the demographic dividend that boosted production for many years has come to an end in most advanced economies. In these economies demographic and labour market factors, such as the falling share of the working-age population in total population, and declines in participation rates in some age/gender groups, are now exerting downward pressure on growth in output per capita.

If: Y = GDP; N = Population; L = Number of workers; Hr = Total annual hours worked
Then: Y/N = Y/Hr x Hr/L x L/N
Or: GDP per capita = Hourly output x Annual hours per worker x Participation rate

Thus, if growth in labour productivity (Y/Hr) is minimal or flat and demographic factors are acting to depress the labour force participation rate, then living standards can rise only if hours worked per worker rises. MFP growth is a particularly critical component of productivity growth as, in its absence, living standards can only be raised via a continued intensification of inputs.

The reasons for this secular decline have been extensively analyzed and debated, and a number of potential explanations have been advanced. The synchronized and longstanding nature of the decline in productivity growth across, first, advanced economies and, subsequently, emerging economies, signals that factors of global scope and extended duration are likely implicated.

Many of the explanations put forward have centred on the role of multifactor productivity -- to which, as noted, much of the decline in productivity growth has been ascribed. Because MFP has historically been the primary driver of productivity, much effort has been directed towards disentangling its components.

In the 1970s and 1980s a great deal of attention was devoted to the impact of the 1973-74 and 1979-80 oil price shocks, particularly to the need they engendered to rapidly adapt or replace energy-intensive productive capital to mitigate rising energy costs, with related negative productivity impacts, particularly for MFP (e.g. Baily, 1981). The two oil price shocks, which together raised real oil prices sixfold over the course of the 1970s, were widely viewed as key factors leading to the productivity slowdown at that point.[6]

A later explanation, notably articulated by Robert Gordon, is that the innovations with the greatest impact are now well behind us, and subsequent innovations have not proved to be as transformative (Gordon, 2012, 2013). Gordon postulated that the innovations of the first and second industrial revolutions drove two major waves of productivity growth spanning two centuries, from 1770 through 1970. He argued that these innovations provided the basis for a powerful, 80-year boost to MFP growth that peaked in the 1940s and did not dissipate until 1970. He observes that average US MFP growth from 1970-2012 was barely one third of that realized over the 1920-1970 period, despite the advances of the information and communications technology (ICT) revolution and their impact on business practices – computerization, robotics, data analysis, ATMs, smart phones, bar codes, etc. He postulates that the major impacts of the ICT revolution had largely been realized by 2005, and that subsequent innovation has had less impact on productivity.

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[6] Of note for the arguments in this paper, a similar productivity impact would have been expected from a sudden depletion of oil reserves, which would also lead to an oil price spike.

Bergeaud *et al.* examined the productivity performance of seventeen developed countries between 1890 and 2015; their findings aligned broadly with Gordon's thesis of two major waves of productivity growth during this period corresponding to the impact of innovation (Bergeaud *et al.*, 2016, 2017). They investigated the impact of education level, average age of equipment, and technology diffusion and found that while these variables had some explanatory value, much of MFP growth still remained unaccounted for (Bergeaud *et al.*, 2016, 2017a, b). Others have advanced a related hypothesis that lags between new innovations and their widespread adoption into production processes may result in significant delays between these innovations and related productivity impacts (Brynjolfsson *et al.*, 2018). Still other explanations have focused on factors such as: sectoral shifts from higher productivity to lower productivity sectors; business dynamism and firm-level dynamics; mismeasurement of output or factors of production; diffusion of innovation from the highest to lowest performing firms; and insufficient aggregate demand (Summers, 2014, 2015).

Bloom *et al.* examined the productivity impacts of research in a range of industries and found that, while research effort has been rising substantially, its productivity impacts have declined sharply, suggesting – consistent with Gordon's hypothesis – that returns to innovation are diminishing (Bloom *et al.*, 2020).

This report sets out an alternate explanation for declining productivity growth. It postulates that ongoing environmental degradation has become a significant driver of declining productivity growth in recent decades. This environmental damage can be measured in economic terms as degradation of natural capital, comprising climate change, biodiversity loss, pollution and waste, and resource depletion.

The foundation of all economies is natural capital, defined here in accordance with the United Nations Environment Program (UNEP) definition, 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, 2023c). Natural resources include all resources, living and abiotic, renewable and nonrenewable, such as soil, water, air, forests, plants, fish, wildlife, minerals and fossil fuels. Ecosystem services include processes such as oxygen generation, climate regulation, rainfall, pollination, carbon storage, flood protection, air and water filtration, waste decomposition, and provision of habitat for fisheries and wildlife.

Production – and hence productivity – is clearly heavily reliant on natural systems and resources. This is most apparent 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 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 and metals. Ecosystem services provide the basic support services for all life and are therefore the essential underpinning for all human activities.

Separate assessments by Price Waterhouse Cooper and Swiss Re have found that over half (55%) of global GDP is generated by industries that are either highly or moderately dependent on nature (Evison *et al.*, 2023; Swiss Re, 2020). Among industries with less direct dependence on nature, there are significant indirect dependencies through supply chains.

The European Central Bank (ECB) has determined that 72% of non-financial corporations in the Euro area are highly dependent on at least one ecosystem service (Boldrini *et al.*, 2023). And the Banque de France found that 42% of securities, by value, held by French financial institutions were highly or very highly dependent on services generated by natural capital (Svartzman, 2021). A comparable study by the Dutch National Bank found that 36% of the investments held by Dutch financial institutions were highly or very highly dependent on one or more ecosystem services (Van Toor *et al.*, 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. This is largely for two reasons. First, 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 and has generally been viewed as a "free" public good.[7] Second, natural capital was traditionally viewed as being of such enormous magnitude as to be impervious to human actions, and therefore effectively limitless and unchanging. Accordingly, it was often viewed as a "given" endowment.[8] However, because natural capital has not generally been counted as a productive capital asset, its role in the economy has been largely invisible and its economic importance heavily devalued, giving rise to significant externalities and distorted economic incentives.

Extensive evidence indicates that human activities have resulted in significant erosion of natural capital in recent decades and that this erosion has been of sufficient magnitude to exert sustained and pervasive downward pressure on productivity growth worldwide. As conventional production functions and economic frameworks do not include natural capital, some of this downward pressure has been apparent in the multifactor productivity "residual" as declining MFP growth rates, while some is apparent in declining labour productivity growth rates.[9]

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

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

[8] Natural capital has not always been excluded from economic frameworks. Both the physiocrats and the classical economists explicitly included land as a factor of production

[9] The most widely used production function, the Cobb-Douglas, is typicaly formulated with output as a function of only two inputs, capital and labour. The Cobb-Douglas is now nearly a century old but is still the basis of many economic models.

these, produced by the United Nations Environment Program (UNEP), show 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 and output 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 further depress productivity growth.

3. The Role of Natural Capital in Economic and Productivity Growth

Many economic historians have concluded that human living standards did not materially rise for many millennia, perhaps as long as 100,000 years – a phenomenon dubbed the 'Long Stagnation' (Susskind, 2024). However, in the past few centuries this long stagnation came to an end. GDP per capita began to rise, initially in Western Europe and then elsewhere, slowly at first and then at an accelerating pace, resulting in unprecedented growth in output and income per person that generated the highest levels of economic prosperity in human history.

After such a long period of close to nonexistent growth, what changed? What factors provided the impetus for the growth acceleration that began sometime after 1500? Theories of economic growth have primarily focused on the roles of physical capital, human capital, and innovation and technology, i.e. the elements of conventional production functions. These factors have all clearly been important. However, little attention has been paid to the role of natural capital – largely because both the concept of natural capital and serious efforts to measure it are relatively recent. It is time to rethink theories of economic growth and to incorporate into them the significant explanatory power of natural capital. This report argues that a compelling case can be made that natural capital is a pivotal variable in the rise and subsequent fall of global productivity growth.

It is posited here that over a period of some four centuries, from around 1500 to the middle of the 20th century, the growing exploitation of natural resources and the natural environment were key catalysts for rising productivity and the associated global growth take-off. Expanding travel and trade initially permitted a growing quantity and range of resources to be brought into economic production, while also providing an escape valve from the growth constraints of localized resource depletion. Later, energy derived from fossil fuels fueled industrial and infrastructure growth and enabled the development of new technologies. During this period, resource depletion and environmental damage occurred, but generally not on a global scale, and the overall scale of damage remained within the regenerative capacity of Earth systems.

However, sometime after the middle of the 20th century, human economic activity began to progressively surpass the Earth's regenerative capacity. That is, we collectively began to run a growing natural capital deficit, with net erosion of natural capital occurring as subtractions from natural capital exceeded regeneration by progressively larger amounts. Since that point, it is argued here that accumulated and accelerating damage to the natural capital foundation of all economies has increasingly slowed productivity growth and, accordingly, economic growth.

Prior to 1950: the frontier economy

Two key factors enabling the growth of the global market economy prior to the mid-20th century were: 1) an expanding frontier, and trade permitting enhanced access to a growing range of natural resources; and 2) rising use of fossil fuels.

Many of the productivity gains of the past few centuries can be attributed, not just to impressive realized gains in technology, human capital and produced capital, but also to an enormous expansion of the de facto resource base – or natural capital – available to market economies, initially through colonization and, later, trade with the Americas, Asia and Africa.

In the late 1400s, the advent of significant intercontinental maritime travel – particularly European travel to other continents – gave impetus to a rapid expansion of maritime trade. Between 1500 and 1800, global maritime trade expanded by an average of 1% per year, with a 23-fold expansion in the quantity of goods transported by ship (Frankopan, 2023). Growth was particularly rapid in the Atlantic, with trans-Atlantic voyages rising from a handful per year prior to 1500 to over 800 annually by 1800 (Acemoglu, Johnson and Robinson, 2005).

The Americas and their surrounding waters afforded European market economies access to:

- Old-growth forests that provided abundant high-quality timber for construction of ships and buildings;
- Whales that provided fuel oil, meat and whalebones;
- Cod so plentiful that Champlain said one could practically walk on the water (Hackett, 2009);
- Fur-bearing animals;
- Arable land;
- Novel plants such as squash, tobacco, potatoes, cocoa, corn, tomatoes, peanuts, cotton, indigo, rubber and vanilla;
- Metals and minerals.

Similarly, Asia provided access to: the spice trade; tea and coffee; porcelain; tropical fruits; silk and other textiles. While Africa afforded access to a range of resources including: metals and minerals; ivory; and diamonds.

Ready access to these resources, combined with high potential profits, fuelled rent-seeking behaviour and rapidly growing commercial exploitation. Colonization served to free European seafaring nations from domestic resource constraints by vastly expanding the scope and reach of resource availability. Indeed, the colonial powers' exploitation of land, resources and commodities in other parts of the world – often at the expense of indigenous populations – has been described as exporting resource depletion (Diamond, 2005; Frankopan, 2023). For example, European demand for tens of millions of Canadian beaver pelts in the 1700s was partly due to European beavers having previously been hunted almost to extinction (Diamond, 2005) – and resulted in turn in large declines in the North American beaver population, to extirpation in some places. Similarly, access to timber in the Americas enabled some European economies to escape many of the consequences of widespread domestic deforestation.

The resources that were thereby accessed directly supported European economic growth that would not otherwise have been possible; while the enormous profits and rents they generated enabled capital accumulation that drove further investment and growth.[10]

Nobel laureates Acemoglu, Johnson and Robinson present evidence that the sustained and historically unprecedented growth acceleration experienced by Western Europe between 1500 and 1800 was driven "almost entirely" by the expansion of trans-Atlantic maritime trade (Acemoglu, Johnson and Robinson, 2005). GDP per capita nearly doubled among European Atlantic trading nations between 1500 and 1820, compared with growth of less than 30% in eastern Europe and the rest of western Europe, and minimal change elsewhere (Chart 8).[11] Acemoglu *et al.* also document a 100-fold increase in the annual profits generated by trans-Atlantic trade during this period for European traders.

This growth later spread to eastern Europe and eventually to the rest of the world, as trade flows expanded globally and the planet industrialized (Charts 8 and 9).

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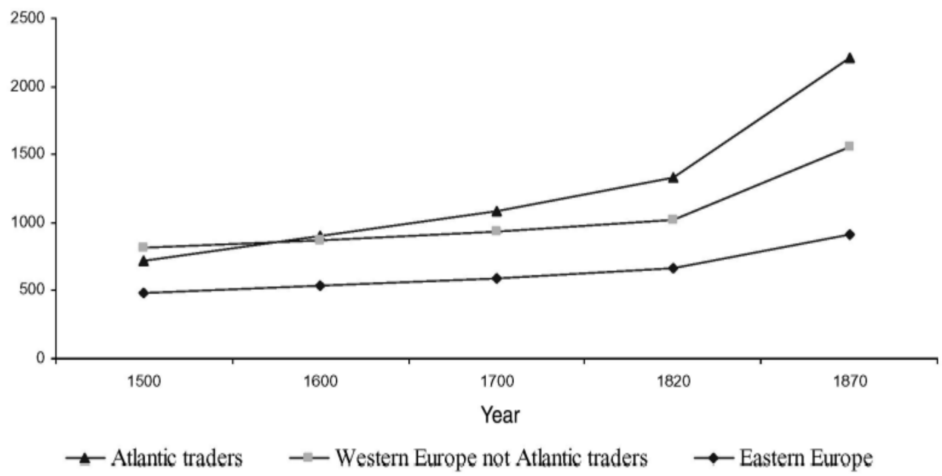
[10] At the same time, however, surging demand for these resources generated severe pressures on plant and animal life in colonized areas, leading to rapid extinctions and near extinctions of a number of previously abundant species including passenger pigeons, right whales, sea otters and plains bison, or buffalo. The passenger pigeon went from being possibly the most numerous bird in the world in the early 1800s, with a population estimated at three billion, to complete extinction by 1914 (Biello 2014). Similarly, the plains bison went from an estimated population of 35 million at the beginning of the 19th century to near extinction by the beginning of the 20th century. Thousands of North Atlantic right whales were also hunted over a three-century period, until there were too few whales to hunt; their population reached a low of just 100 in the 1930s. Sea otters were hunted on the Pacific west coast for the fur trade, resulting in a decline in their population from 150,000-300,000 to only about 2,000. Extinctions following waves of human arrivals are not a new phenomenon but date back to prehistoric times: "Whenever humans arrived and settled in an area, the largest animals consistently and quickly disappeared. The expansion of modern humans in Eurasia led to the extinction of 35% of megafauna. Australia, North America and South America were particularly hard-hit, respectively losing, shortly after humans arrived, 88%,83% and 72% of their megafauna. Megafauna species were hunted to extinction either for their value as a food source, given prehistoric humans' reliance on game meat, or because they posed a threat and competed for resources." (Lambertini et al. 2025). Overall, it is estimated that human activity likely led to the elimination of half the megafauna species globally in the Pleistocene and early Holocene, between ≈50,000 and ≈3000 years ago (Greenspoon et al., 2025).

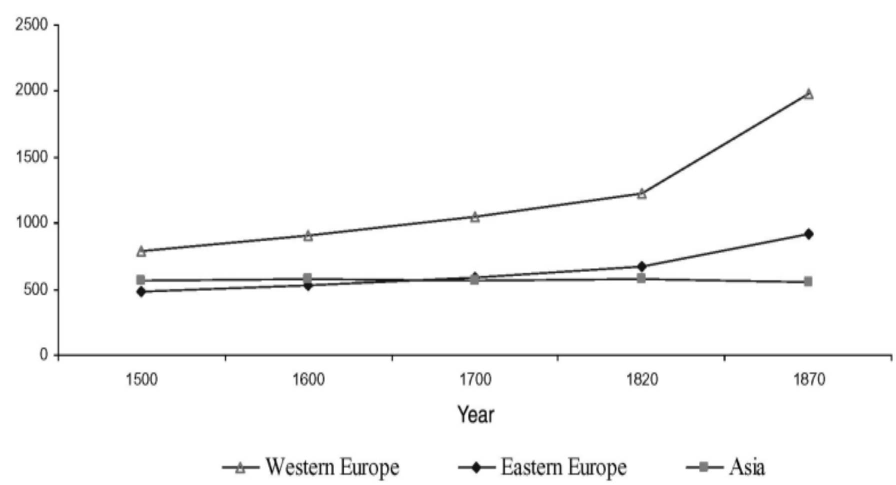
[11] Atlantic trading nations are defined as Britain, France, the Netherlands, Portugal, and Spain; Atlantic trade includes trade with the Americas and with Asia via the Atlantic. GDP per capita figures were drawn from Angus Maddison (2001*) The world economy: A millennial perspective.* Paris: OECD, Development Center.

Chart 8: GDP per capita, weighted by population, 1500-1870



Source: Acemoglu, Johnson and Robinson (2005) and A. Maddison (2001)

Chart 9: GDP per capita, weighted by population, 1500-1870



Source: Acemoglu, Johnson and Robinson (2005) and A. Maddison (2001)

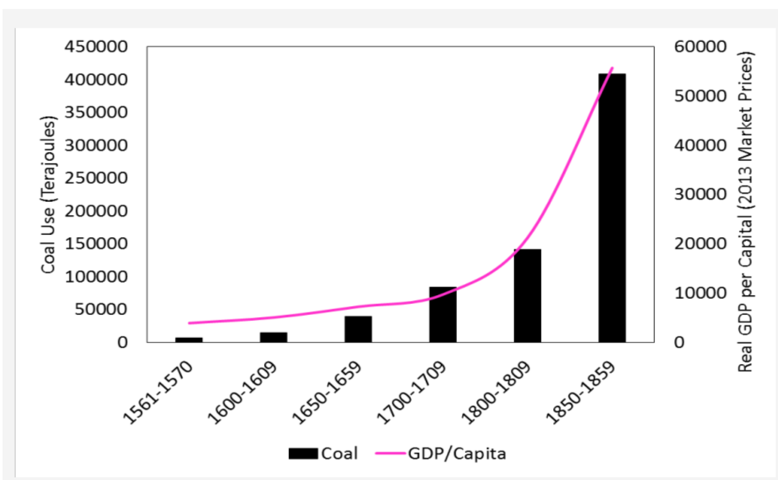
The other, later enabler of economic growth – specifically, the surges of growth generated by the first and second industrial revolutions – was the transition to fossil fuels – first coal, then oil and gas. The first industrial revolution (1770-1840) encompassed the development of coal-powered steam engines, railroads, steamships, and cotton spinning and weaving, providing a large spur to productivity growth, with ongoing impacts throughout the 19th century. Subsequently, the second industrial revolution (1870-1920) introduced: the internal combustion engine, which enabled the wide diffusion of car and truck transportation and aviation; electricity, which powered productive machinery and lit workplaces; and chemicals and plastics.

The steam engine was invented in 1769 and the cotton gin, which separated cotton fibres from seeds, in 1793. The steam-powered cotton ginny transformed textile manufacturing and was one of the first technologies to enter into widespread use during the first industrial revolution. However, its widespread adoption in England depended, in the first instance, on the availability of imported cotton – a plant unknown in Europe before the advent of trans-Atlantic travel and one which was not well suited to European growing conditions. Cotton imports from the United States rose ninety-three times between 1791 and 1800 and another seven times between 1800 and 1820 (Frankopan, 2023). The other key enabling factor was an efficient energy source, in the form of coal.[12]

Coal was quickly adopted as a source of energy for other innovations – first railroad engines and later steamships. Demand for coal in Britain grew rapidly, from 11-15 million tonnes per year in 1800 to 100 million tonnes by 1870, as it displaced energy derived from wood, water and animals and came to account for over 90% of energy consumption (Pirani, 2018; Wrigley, 2013). Coal-powered ships and railways permitted much higher volumes of goods to be transported between continents and within countries, further facilitating resource access.

The expanded energy access afforded by coal is essentially inseparable from the technological advances of the first Industrial Revolution as instrumental in spurring a wave of productivity growth in industrializing countries. All of the key innovations of the first industrial revolution required coal power to function. Elkomy, Mair and Jackson note the close correspondence in the growth trajectories of English coal use and GDP per capita between 1651 and 1859 (Chart 10). Coal provided access to millions of years of accumulated carbon, thereby freeing economies from the growth constraints imposed by the inherently limited renewable energy sources of the time.

Chart 10: English coal use and GDP per capita, 1561 to 1859



Source: Elkomy, Mair and Jackson (2020)

The expansion of energy access continued during the second industrial revolution, in which the central innovations also relied on fossil fuels – whose usage grew rapidly and shifted increasingly towards oil and gas. The internal combustion engine, which permitted exponential

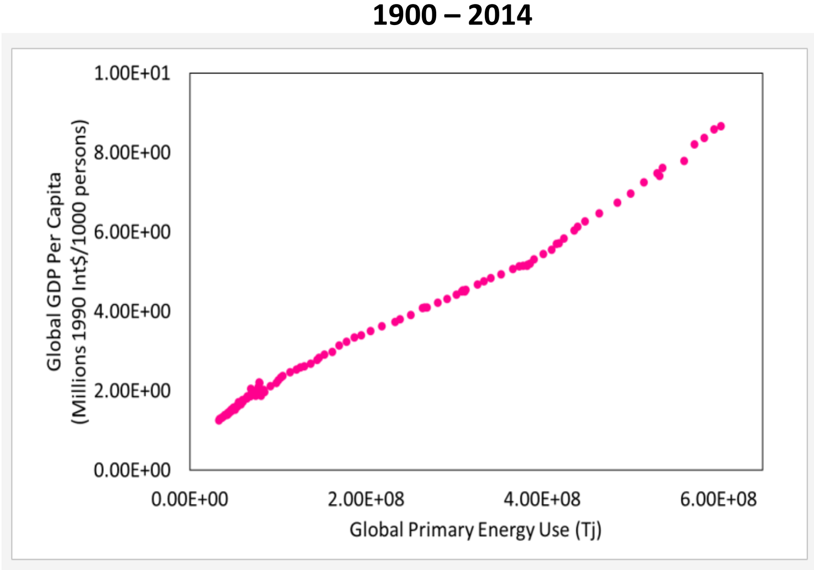
[12] While beyond the scope of this paper, it is also important to acknowledge the role played by slavery in generating production of cotton and many other products on the basis of human exploitation and misery.

growth of road and air transportation, was of course fueled by gasoline. The electricity that powered many manufacturing industries was initially derived from coal and water, and later from gas. And in the 20th century the burgeoning chemical industry, whose products included fertilizers that enhanced agricultural productivity and plastics that enhanced trade by revolutionizing packaging, relied heavily on inputs from fossil fuels.

Between 1800 and 2000 global population grew by six times, energy use by forty times, and the global economy by fifty times (Steffen *et al.*, 2008). A number of economists and economic historians have made the case that energy-related innovations and growth in the quantity and quality of available energy are crucial in explaining the economic and productivity growth that ensued from the first two industrial revolutions (e.g. Frankopan, 2023; Wrigley, 2010). Stern and Kander assessed two centuries of Swedish growth (1800-2000) using a neoclassical growth model extended to include energy, and found that the expansion of energy services was the single most important factor explaining growth from 1800-1950 – after which labour-augmenting technical change became paramount (Stern and Kander, 2012).

Historically, labour productivity growth and energy use have consistently been shown to have been closely correlated over the long run.[13] Elkomy, Mair, and Jarvis show that the growth rates of global GDP per capita and global primary energy use were essentially identical throughout the 1900s (Chart 11). Levels of output per capita and energy use per capita were also historically closely correlated in inter-country comparisons (e.g. Meadows *et al.*, 1972).

Chart 11: Relationship between global primary energy use and labour productivity, 1900 – 2014



Source: Elkomy, Mair and Jackson (2020)

Accordingly, while innovation – in combination with investments in physical and human capital – was certainly an important driver of both the first and second industrial revolutions, neither revolution could have happened without: 1) the huge de facto expansion of natural resource

[13] In this century, there is significant evidence of a 'decoupling' of this linkage in advanced economies (Section 9).

availability afforded first by colonization and later by rapid growth in international trade; and 2) the vast quantities of energy derived from fossil fuels. This expanded access to natural capital provided a sustained productivity boost to market economies from the early 16th century through the mid-20th century.

While there was certainly related erosion of natural capital during this period – as fish were caught, animals hunted, trees felled, and stocks of minerals and fuels depleted – this occurred on a more modest scale than was the case after the mid-20th century. Global population and the size of the global economy were both much smaller. Most waste was organic and could therefore be decomposed by natural systems. The destructive impacts of accumulating greenhouse gas emissions were not yet apparent. Accordingly, while damage to the natural environment certainly occurred, the scale was smaller and, therefore, more regeneration of renewable resources and ecosystems was possible. The economic benefits of growing natural capital usage – which largely accrued privately – apparently outweighed the shared costs of environmental damage.

Post-1950: the spaceship economy

Over the past century, and particularly over the past fifty years, the demands of human economic activity on the natural environment have accelerated rapidly. Since the early 1970s global population has doubled from 4 billion to over 8 billion, world GDP has quadrupled and global trade has grown tenfold (IPBES, 2019). Global material extraction from the natural environment has risen accordingly, from an estimated 7 billion tonnes (7 Gt) per year in the 19th century to 31 Gt by 1970, and 107 Gt by 2024 (Krausmann *et al.*, 2009; Vienna University, 2025).[14] In addition to the significant environmental impacts from the annual extraction of 107 billion tonnes of material from the planet are those associated with the subsequent disposal of this massive volume of material, whether as production by-products, pollution or waste at the end of the consumption life-cycle.

A growing body of scientific evidence indicates that in the second half of the 20th century the rapidly expanding scale of human impacts on the natural environment began to outstrip the environment's capacity for regeneration. In other words, human economic activity began to bump up against planetary constraints, creating a growing awareness in some circles that resources that had previously been viewed as essentially infinite and unchanging did in fact have limits and could be altered by human activity.

This has been described as a transition from what had been 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 where planetary limits were becoming increasingly apparent – a spaceship economy, requiring a different set of economic principles (Boulding, 1966).[15] The growing awareness of the economic implications of this transition sparked a rich literature in the 1960s and 1970s by

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[14] Since 1970, the increase in global resource extraction has been driven in approximately equal parts by population growth and higher GDP/capita, while technological change has acted to partially offset these drivers (UNEP, 2024a).

[15] This transition was initially described by Kenneth Boulding, who used the terms 'cowboy economy' and 'spaceman economy'.

authors including Kenneth Boulding, Donnella and Dennis Meadows, Herman Daly, Garret Hardin and E.F. Schumacher (Boulding, 1966; Daly, 1973; Hardin, 1968; Meadows *et al.*, 1972; Schumacher, 1973).

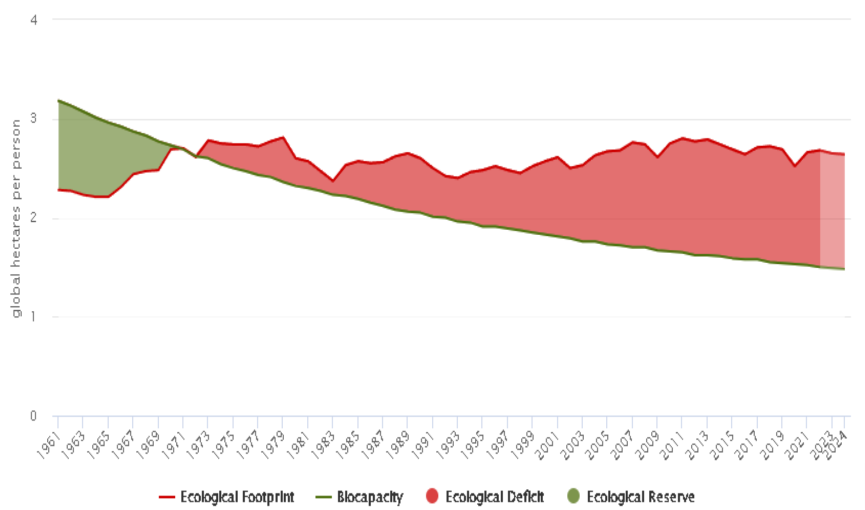
The scientific evidence that natural systems and resources were increasingly encountering hard limits after the middle of the 20th century includes a range of indicators.

Environmental footprint

Environmental footprint analysis compares the Earth's biocapacity – the sustainable capacity of its ecosystems – with the demands placed on it by humans (Wackernagel & Rees, 1995). This analysis has found that humans collectively began to exceed the ability of Earth to provide resources sustainably around 1970, and now annually use the equivalent of what 1.8 Earths could sustainably provide (Global Footprint Network, 2025).[16] In other words, humans have exceeded the Earth's biocapacity since that point.

Chart 12 graphs the human environmental footprint per capita against the Earth's biocapacity per capita. It shows that prior to 1970 the Earth's biocapacity per person exceeded the demands made on it per person, i.e. there was an "ecological reserve". Since 1970, per capita human demands have exceeded the Earth's biocapacity by a growing margin, resulting in a widening "ecological deficit" that can be viewed as analogous to a natural capital deficit.

Chart 12: Global ecological footprint and biocapacity per capita



Source: Global Footprint Network (2025)

Living Planet Index

The Living Planet Index, constructed by the World Wildlife Fund, tracks changes in the relative abundance of wild species over time, based on monitoring of 35,000 populations worldwide

[16] Note that this ratio can be altered by changes to either the numerator or denominator; that is by the level of human demand, or by changes in the earth's biocapacity.

representing 5,495 species of birds, mammals, fish, reptiles and amphibians (WWF, 2024).[17] Globally, the average drop in population abundance between 1970 and 2020 was a startling 73%; for Latin America and the Caribbean, the decline was even greater, 95% (WWF, 2024). Terrestrial populations have declined by an average of 69% since 1970; freshwater species by an average of 85%; and marine species by 56% (IPBES, 2019; WWF, 2024).

The Anthropocene epoch and the "great acceleration"

Nobel Laureate Paul Crutzen introduced the concept of the Anthropocene in 2000, based on the assertion that the impact of human activities on the Earth had grown so great as to become a global geophysical force rivalling natural forces (Steffen *et al.*, 2008). He proposed that Earth had left its previous geological epoch, the Holocene, and entered a new epoch he named the Anthropocene (Stefffen *et al.*, 2008):

> "Preindustrial societies … did not have the numbers, social and economic organization, or technologies needed to equal or dominate the great forces of Nature in magnitude or rate. Their impacts remained largely local and transitory, well within the bounds of the natural variability of the environment. … Over the past 50 years, humans have changed the world's ecosystems more rapidly and extensively than in any other comparable period in human history." (Steffen *et al.*, 2008)

In support of this idea, Steffen *et al.* set out the thesis that since 1950 multiple indicators provide clear evidence of a 'great acceleration' in the impact of humans on the Earth system: "While it is certainly true humans have always altered their environment, sometimes on a large scale, what we are now documenting since the mid-20th century is unprecedented in its rate and magnitude." (Steffen *et al.*, 2015)

This conclusion was endorsed by the IPBES: "Direct and indirect drivers of change [in nature] have accelerated during the past 50 years. The rate of global change in nature during the past 50 years is unprecedented in human history." (IPBES, 2020)

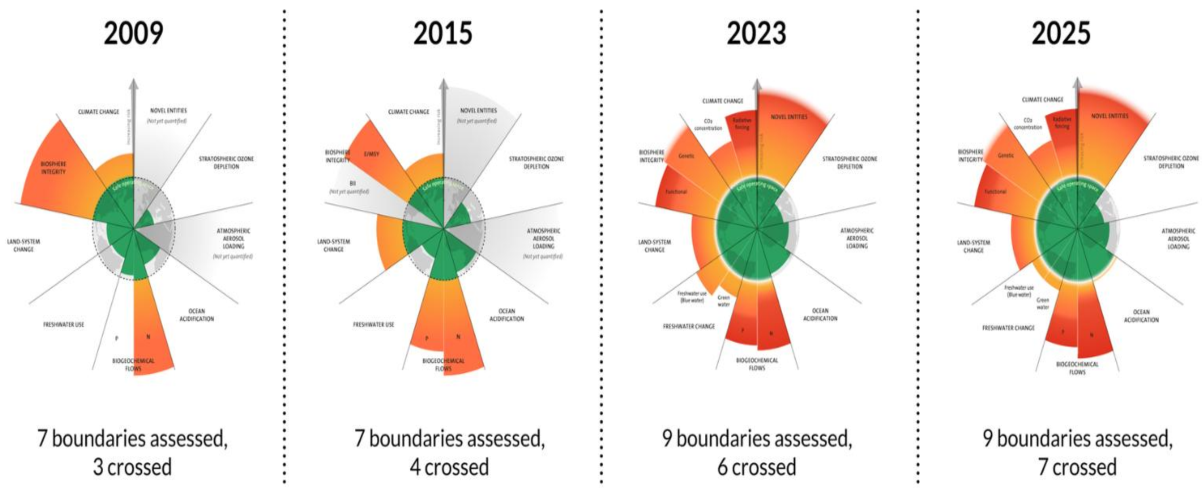
Planetary boundaries framework

The planetary boundaries framework, set out in 2009 by an international team of scientists based at Stockholm University, was developed to identify a scientifically-based safe operating space for humanity. It identified key systems critical to the stability of the overall Earth system, and quantified for each a boundary that should not be crossed in order to avoid unacceptable global environmental change. In 2009, seven of the nine boundaries were assessed, with the finding that three of these seven had already transgressed safe limits – climate change, biosphere integrity and biogeochemical flows (e.g. the water cycle and carbon cycle) (Rockstrom *et al.*, 2009). By 2023, all nine systems had been assessed, and three more systems had moved beyond the planetary safe space – land use, freshwater change and synthetic pollutants – leading the scientists to conclude that, with six of nine boundaries transgressed, Earth was "well outside of the safe operating space for humanity" (Chart 13) (Richardson *et al.*, 2023). In 2025 it was found that a seventh system, ocean acidification, had breached the boundary in 2020,

[17] A population is a group of individuals of the same species within a specific geographic area.

leaving only two – ozone depletion and atmospheric loading – well within the safe zone (Caesar *et al.*, 2024; Findlay *et al.*, 2025).

Chart 13: Evolution of the planetary boundaries framework, 2009-2025



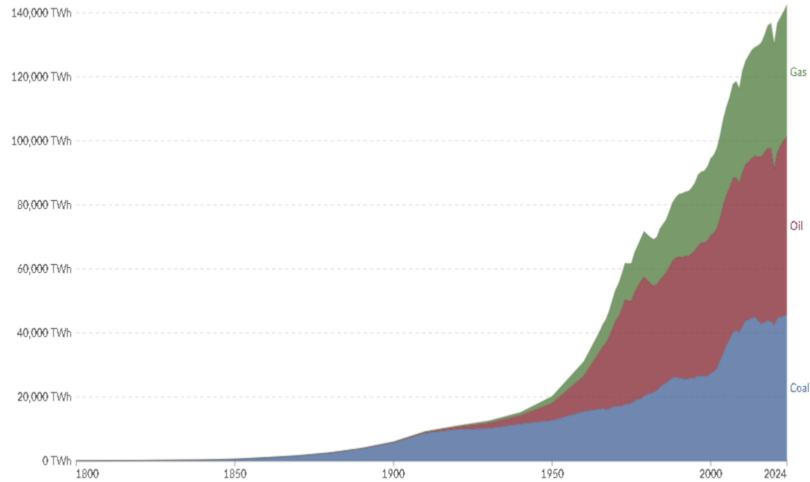
Source: Stockholm Resilience Centre, Stockholm University, 2025

Climate change

Human civilization evolved and flourished during the Holocene period, a period of relatively stable, moderate climate that began approximately 11,700 years ago at the end of the last ice age and includes the advent of agriculture approximately 10,000 years ago.

Global fossil fuel consumption has risen nearly sevenfold since 1950, growing from 20,100 terawatt hours (TWH) in 1950 to 142,400 TWH in 2024, with comparable related increases in greenhouse gas (GHG) emissions (Chart 14). Accordingly, the 350 ppm of carbon dioxide upper limit associated with maintaining global climate within the safe Holocene zone was breached in the late 1980s, driving global warming and associated climate change (NOAA, 2024c). Approximately half of all GHG emissions have occurred since 1988 – a year which coincides with the beginning of widespread awareness of climate change, following 1988 testimony by NASA climate scientist James Hansen to the US Senate that fossil fuels were producing a greenhouse effect resulting in global warming (IPCC, 2023; Shabecoff, 1988).

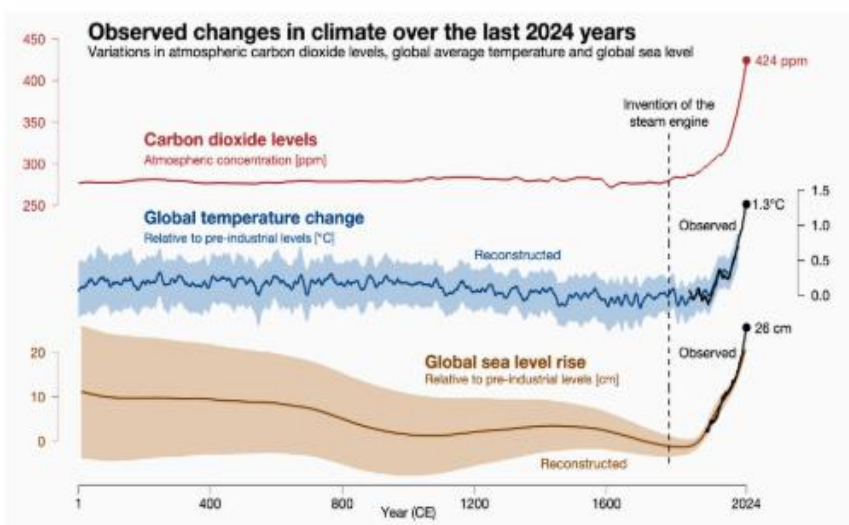
Chart 14. Global fossil fuel consumption, 1800-2024
Terawatt-hours of primary energy consumption



Source: Energy Institute – Statistical Review of World Energy (2025); Our World in Data (2025)

The impacts of climate change have become readily apparent only since the 1980s. In 2024, the Earth reached, for the first time, an annual global air temperature of more than 1.5°C above pre-industrial levels (1850-1900) (Copernicus, 2025; WMO, 2025b). Over two thirds of this increase has occurred since 1980 (Chart 15). Rising global temperatures have been accompanied by sharply higher incidences of the most severe hurricanes and tropical cyclones (Categories 3-5); of extreme precipitation events leading to flooding; and by more frequent and prolonged droughts, which have been linked to a rising incidence of severe wildfires. In addition, the average rate of sea level rise has accelerated from 1.3 mm/year 1901-1971 to 1.9 mm/year 1971-2006 and 3.7 mm/year 2006-2018, for a cumulative total of 26cm, leaving coastal cities and communities more vulnerable to flooding (IPCC, 2023).

Chart 15: Climate change indicators, 1-2024 CE



Source: Hawkins, 2025a

Natural capital: from productivity booster to productivity drag

Robust productivity growth, then, was maintained for an extended period of time in large part by reliance on fossil fuels – at the eventual expense of a stable climate – and by broadening access to many other resources.[18] 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 then 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.

Ronald Wright described these two stages of our economic interaction with natural systems as: 1) the economy exacting loans from nature and 2) nature foreclosing on the loan (Wright, 2004).

In short, today's declining productivity growth results at least in part from ongoing depletion of natural resources and ecosystems; this depletion often requires ever-increasing offsets in the form of investments in physical capital.[19]

Emerging and developing economies

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 currently 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.

Emerging and developing economies generally have more unexploited opportunities than advanced economies. They are lower on the production curve and still exploiting their most productive assets, and therefore have not encountered the zone of diminishing marginal productivity to the same extent as advanced economies. For example, investments in expanding primary education have greater marginal productivity impact than those in postsecondary education. Therefore, even if natural capital losses are acting to depress productivity gains in

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[18] Natural capital supported productivity, of course, in conjunction with the three generally recognized factors of physical capital, human capital and technology.

[19] An analogy would be a manufacturer that had surplus capital equipment capacity and therefore undertook no maintenance, repair or investment – as one machine broke, simply moving on to the next. In the short term, it might experience an apparent productivity boost by basing production on capital depreciation, thereby reducing immediate production costs. Over the longer term, however, a point would inevitably be reached when all the machines were malfunctioning or stretched beyond their capacity and productivity would drop. This is effectively what has happened with natural capital. Or, per Joseph Stiglitz: "A company with positive cash flow can be running itself into the ground as its capital depreciates. Economies are no different." (Stiglitz, 2006)

these economies, gains from investment in human capital and produced capital may have been sufficiently large to outweigh this negative impact for a period of time. A recent analysis found that 80% of productivity increases in developing economies over the past 25 years could be attributed to rising produced capital intensity (Mischke *et al.*, 2024). As previously observed, however, growth rates of emerging economies have recently been falling toward those of advanced economies.

In addition, 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 generally higher (UNEP, 2023c; World Bank, 2024b). 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.

4. Scientific Assessments of Environmental Degradation

An overview is provided here of the scientific evidence on environmental degradation that underlies natural capital measurements, in four categories: a) climate change; b) biodiversity and nature loss; c) soil and sub-soil resource depletion; and d) pollution, waste and contamination.

a) Climate change

The Intergovernmental Panel on Climate Change (IPCC) has found that a century of human emissions has caused greenhouse gases (GHGs) to rise to atmospheric concentrations unprecedented in human history, with carbon dioxide concentrations now higher than at any time in the past two million years driving accelerating manifestations of climate change (IPCC, 2023). Human-caused GHG emissions continue to rise, while the rate of natural sequestration of CO2 from the atmosphere by the terrestrial biosphere is declining, having reached a peak in 2008 (Curran & Curran, 2025; Ke *et al.*, 2024, 2025). As a result, the rate of increase in GHG atmospheric concentrations has accelerated (WMO, 2025a).

Global surface air temperatures have risen significantly, averaging 1.1 °C above pre-industrial levels from 2011 to 2020 (IPCC, 2023). In 2024 they reached an annual average of 1.55° C, exceeding for the first time the preferred 1.5° C upper limit under the Paris Agreement for temperature increases (Copernicus, 2025; ECMWF, 2025; WMO, 2025b). 2024 was the warmest calendar year on record for both air and ocean temperatures (Copernicus, 2025; ECMWF, 2025; WMO, 2025b).

Rising air and ocean temperatures produce faster rates of water evaporation and have therefore led to much more frequent extreme weather events, including heavy rainfall and the most severe hurricanes and tropical cyclones, Categories 3-5 (IPCC, 2023). These events have resulted in steeply escalating levels of property damage due to flooding and high winds.

The frequency and intensity of hot extremes have also increased since the 1950s, and 30% of the global population is now exposed to deadly levels of heat for more than 20 days a year

(UNEP, 2024). In addition, hundreds of local species losses have resulted from severe heat extremes (IPCC, 2023).

The incidence and duration of droughts have risen, and water scarcity now affects over half the global population for at least part of the year (Frost *et al.*, 2025; IPCC, 2023). Hotter, dryer conditions have also contributed to rising wildfire incidence, with a doubling in the frequency of extreme wildfire events over the past twenty years (IPCC, 2023; Jones *et al.*, 2024).

These conditions have also resulted in an acceleration of desertification, with increasing soil aridity and decreasing biological activity (IPCC, 2023). Over the past forty years, desertification accelerated to thirty times its historical rate, and over 500 million people lived in areas that experienced desertification (Burrell *et al.*, 2020; IPCC, 2023). Between 1982 and 2015, 6% of the world's drylands – which cover 41% of Earth's land surface – underwent desertification due to a climate change, deforestation and unsustainable land use practices, with Africa and Asia most affected (Burrell *et al.*, 2020).

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).

The ocean has to date absorbed approximately 90% of excess accumulated heat, causing ocean temperatures to rise significantly, to record high levels in 2024 (Copernicus, 2025). Marine heat waves have doubled in frequency over the past forty years, resulting in ecosystem damage including mass mortality events (Copernicus, 2024). Higher ocean temperatures have also led to ocean acidification, damaging shellfish and resulting in the loss of 50% of live coral reef cover (Copernicus, 2024). Melting polar ice has contributed to rising sea levels, raising flooding risks for coastal areas.

In addition, 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).

b) Biodiversity and nature 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 *et al.*, 2006).

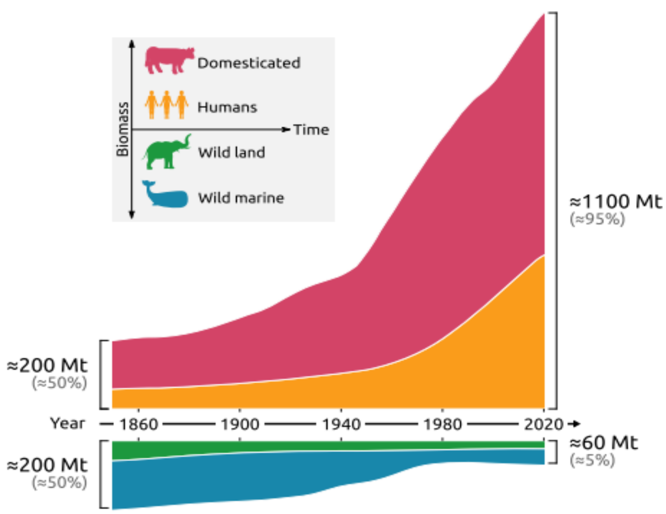
The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) conducts global assessments of biodiversity and ecosystem services on behalf of 140 member states. Its landmark first assessment report concluded that biodiversity is declining faster than at any time in human history, due largely to habitat loss, pollution and climate change (IPBES, 2019).

The IPBES found that human activity has significantly altered 75% of global land area and 66% of the ocean. Over 85% of wetland area has been lost, and land degradation has reduced productivity in 23% of all land. One fifth of global forests, approximately 10M square kilometres, have been lost since 1900, and there have been significant recent losses due to wildfires, with ramifications for the role of forests as carbon sinks, wildlife habitat and regulators of water and temperature.

Nature across most of the planet has been significantly altered, with the great majority of ecosystems showing rapid decline. The integrity of ecosystems has already been compromised in 60% of global land area (Stenzel *et al.*, 2025). Overall, natural ecosystems have declined in size and condition by 47% compared to baselines. A number of ecosystems are reaching hard adaptation limits, including some coral reefs, coastal wetlands, rainforests, and polar and mountain ecosystems (IPCC, 2023).

The global biomass of wild mammals, including marine mammals such as whales, has fallen by 70% since the 1850s (Greenspoon *et al.*, 2025). Wild mammals now comprise only 5% of the global biomass of mammals (down from 50% in 1850), with humans (36%) and domestic livestock (59%) comprising the other 95% (Chart 16). Among birds, wild birds now account for only 29% of total bird biomass, with poultry accounting for the remaining 71% (IPBES, 2019). The total biomass of fish has dropped by 50% and, locally, many populations have been fished to near extinction.

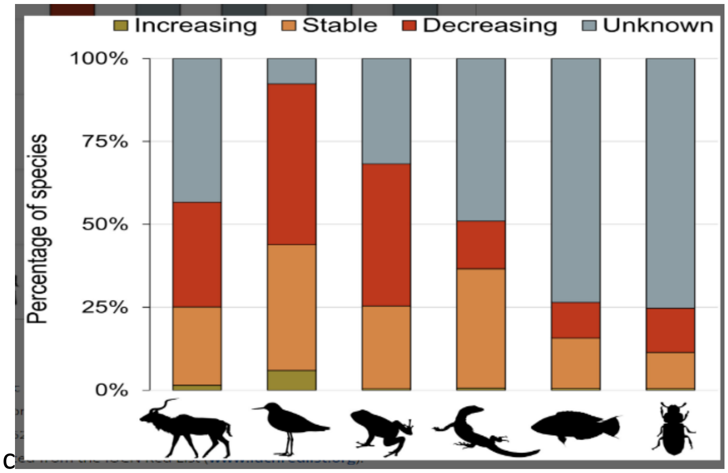
Chart 16: The global biomass of mammals since 1850



Source: Greenspoon et al. (2025)

A recent study of 71,000 animal species spanning mammals, birds, reptiles, amphibians, fish and insects, found population declines in nearly half of all species (Finn *et al.*, 2023): among species with known population trends, 48% of species were undergoing population declines, 49% were stable and 3% increasing (Chart 17). This corresponds to decreasing populations among: 56% of mammal species; 53% of birds; 63% of amphibians; 28% of reptiles; 41% of fish; and 54% of insects (Finn *et al.*, 2023).

Chart 17: Population trends among 71,000 animal species



Source: C. Finn et al. (2023)

These trends have resulted in an overall average 73% decline globally in the population of mammals, birds, fish, reptiles and amphibians since 1970 (WWF, 2024). Global insect populations – the base of many food chains, and responsible for pollination of 87% of all plant species and 75% of all food crops – are dropping even more rapidly, by 58% over just thirty years (1990-2020) (Goulson, 2019; Sanchez-Bayo & Wyckhuys, 2021).[20]

Overall, the IPBES found that approximately one quarter of all known species are currently threatened with extinction, and the current global rate of extinction is unprecedented in human history and tens to hundreds of times higher than the average over the past 10 million years (IPBES, 2019).[21] These trends have led a number of scientists to conclude that the Earth is currently entering its sixth mass extinction event (Ceballos, 2017; Finn *et al.*, 2023; Goulson, 2019; Kolbert, 2014; Sanchez-Bayo & Wyckhuys, 2019).

Of eighteen categories of contributions of nature to humans assessed by the IPBES, fourteen declined over the fifty years between 1970 and 2019 (IPBES, 2019) (Chart 18).[22] While some material contributions rose (agricultural production, fish harvest, bioenergy production and timber), others declined (forested land, marine fish stocks, and medicinal, biochemical and genetic resources). Simultaneous declines in nine out of ten ecosystem services, however, led the IPBES to conclude that rising material contributions are often not sustainable.[23] The three

[20] Studies conducted between 1979 and 2019 showed an annual average global loss of insect biomass of 2.5%, corresponding to a global decline of 74% over forty years (Sanchez-Bayo & Wyckhuys, 2019). At the national level, recent studies have shown even more pronounced declines in insect populations, with insect biomass declines of 76% in Germany over 26 years; 78% in the UK over 20 years; and 75-98% in Puerto Rico over 35 years (Goulson, 2019; Kent Wildlife Trust, 2024).

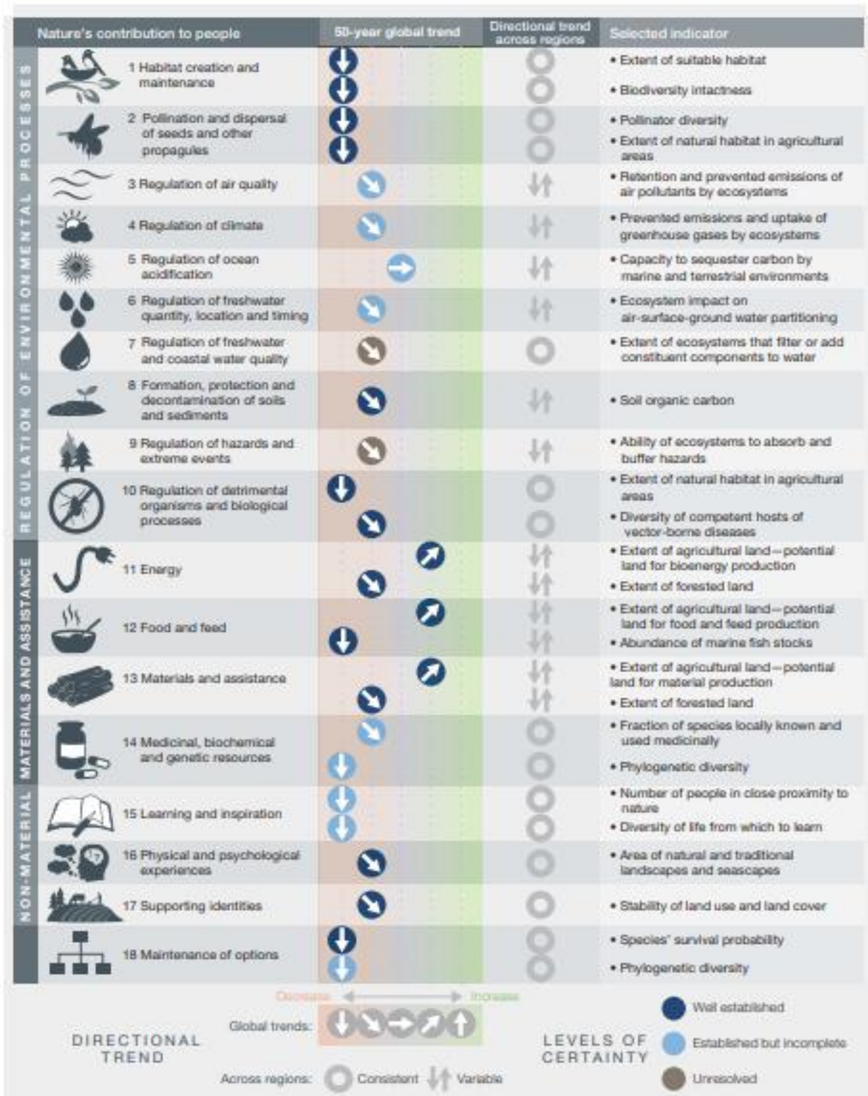
[21] Other sources, e.g. Finn et al. (2023), suggest that the extinction rate is actually 1,000 to 10,000 times higher than background rates.

[22] This assessment was based on a review of 2,000 studies of these trends since 1970 (IPBES, 2019).

[23] The one ecosystem service assessed in the 2019 IPBES report as relatively stable, ocean acidification, has subsequently been determined to have declined steeply (Findlay et al., 2025).

non-material contributions (learning and inspiration, physical and psychological experiences, and supporting identities) also declined, as did maintenance of options.

Chart 18: Global trends in the capacity of nature to sustain contributions to good quality of life, 1970 - 2020



Source: IPBES (2019)

IPBES Chair Robert Watson stated: "The health of ecosystems on which we and all other species depend is deteriorating more rapidly than ever. We are eroding the very foundations of our economies, livelihoods, food security, health and quality of life worldwide" (IPBES, 2019).

The IPBES directly addressed the issue of substitutability for natural capital. It found most contributions of nature are not fully replaceable; while substitutes for some contributions have been created, many are imperfect or financially prohibitive, and human-made replacements generally do not offer the full range of benefits provided by nature. Further, it indicated that some losses of natural capital can permanently reduce future options, and some contributions of nature are irreplaceable. For example, the first ten contributions in Chart 18, regulation of environmental processes, are all either irreplaceable or replaceable only at a prohibitive cost.

c) Soil and sub-soil resource depletion

Groundwater depletion

Groundwater is heavily relied upon as a water source throughout much of the world, often for agricultural irrigation. It is particularly valuable when rainfall levels are low or erratic, as is increasingly the case due to climate change. However, demands from rapidly growing populations and water-intensive industries are depleting underground aquifers in many places; groundwater declines occur when withdrawals exceed replenishment, or recharge. While some groundwater is technically a renewable resource, the timescale for replenishment can be excessively long for relevance to human needs, in the range of centuries or millennia (Jasechko *et al.*, 2024). Therefore, some scientists take the position that when groundwater depletion occurs, groundwater is no longer exploited as a renewable resource but as a nonrenewable one (Doll *et al.*, 2014). Further, approximately 15% of worldwide groundwater withdrawals between 2000 and 2009 were taken from nonrenewable sources (Doll *et al.*, 2014).

Recent analysis of 1,693 aquifer systems covering three quarters of global groundwater withdrawals found that rapid groundwater level declines since 1980 are widespread, occurring in nearly half (48%) of these aquifers, and that declines have accelerated over the past four decades in of one third of the aquifers (Jasechko *et al.*, 2024). A separate study estimated that the rate of global groundwater depletion after 2000 was more than double the rate during the 1960-2000 period (Doll *et al.*, 2014). Most of the aquifer systems showing accelerating groundwater declines were in areas experiencing declining average precipitation over time, suggesting that climate change may be acting to both raise water demand and simultaneously reduce supply by slowing aquifer recharge (Jasechko *et al.*, 2024). Rapidly depleting aquifer systems are most common under cultivated drylands where irrigation-related withdrawals are high (Jasechko *et al.*, 2024).

Soil degradation and erosion

Soil is the foundation of food production. However, a global assessment found that the majority of the world's soil resources are in only fair, poor or very poor condition (FAO, 2015a).

Soil is considered to be a living system. While technically a renewable natural resource it is, like groundwater, renewable only over very long periods; it can take up to 1,000 years to produce 2-3 centimetres of soil (FAO 2022a).

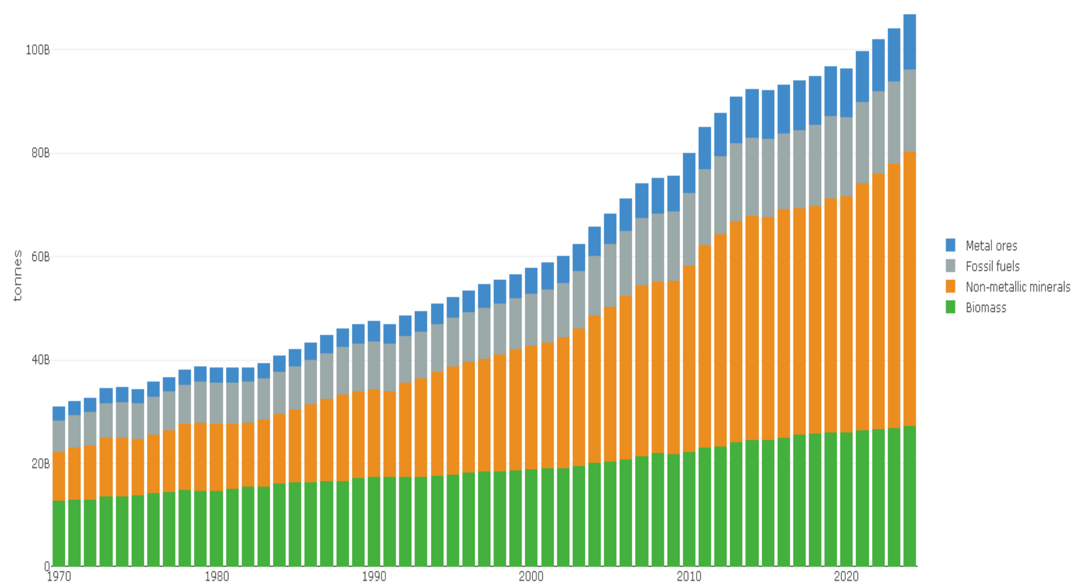
At present, 44% of the earth's habitable land surface (i.e. glacier-free and non-desert) is used for agriculture, including both cropland and pasture (FAO, 2024). However, high rates of soil erosion on agricultural land exceed natural rates of soil formation, causing net annual losses. Rates of soil erosion on arable or intensively grazed lands are estimated at 100-1,000 times higher than natural background erosion rates, resulting in average global soil loss of .9 mm per year – significantly in excess of rates of soil formation (FAO, 2015b). The FAO has observed that this large disparity between rates of erosion and soil formation implies that soil is a non-renewable resource under current conventional agricultural practices (FAO, 2015b).

Accordingly, the FAO has found that one third of global land area, particularly cropland, has degraded soil with reduced productivity, due largely to unsustainable agricultural practices, and that the soil has likely already become depleted in many areas, including around the Mediterranean Sea and in tropical mountain regions (FAO, 2015a, 2021).

Other sub-soil resource depletion

Between 1970 and 2024, total global material extraction from the planet tripled, to 106 billion tonnes. Mining of metal ores quadrupled; that of non-metallic minerals more than quintupled; and fossil fuel extraction grew by 2.5 times (Chart 19).[24]

Chart 19: Global material extraction by type, 1970-2024, Billions of tonnes



Source: Vienna University of Economics and Business (WU Vienna) (2025)

Material extraction has heavy environmental impacts; it frequently leaves behind scarred and contaminated landscapes requiring extensive rehabilitation. Further, extraction of metals,

[24] The particularly rapid growth in non-metallic mineral extraction is largely related to materials used for construction of buildings and infrastructure.

minerals and fossil fuels generally begins with the highest quality and most accessible sources, meaning that the quality and accessibility of remaining reserves typically decline over time.

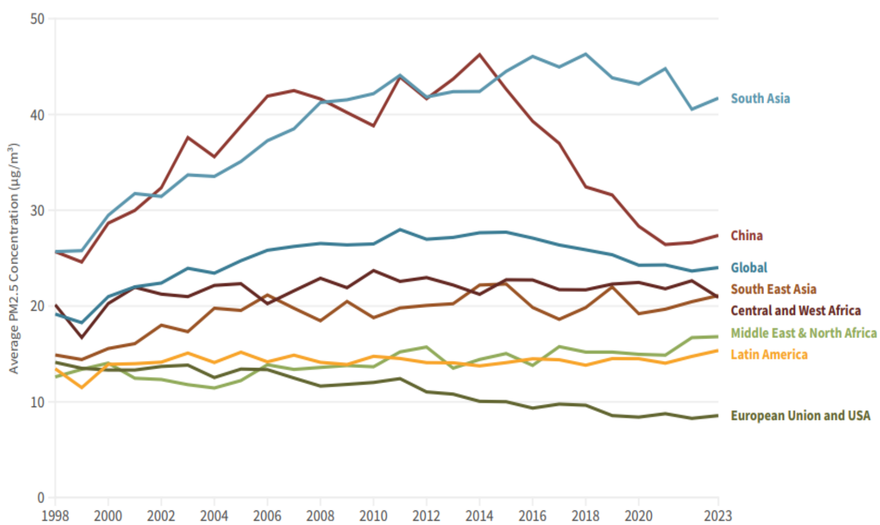
d) Pollution, Waste and Contamination

Pollution and contamination depreciate the natural capital assets of air, water and soil.

The enormous growth of global materials extraction has resulted in related increases in waste generation. Of the 106 billion tonnes of material consumed by the global economy in 2019, 91% was derived from harvesting and extraction and only 9% from recycled and recovered resources (UNEP, 2024a). This consumption stream generated 30 billion tonnes of solid and liquid waste, and 47 billion tonnes of greenhouse gas emissions (UNEP, 2024a).

As materials processing expanded and burning of fossil fuels grew (rising sevenfold since 1950), air pollution worsened accordingly in many locations, with rising concentrations of fine particulate matter and chemicals known to be damaging to human health and to be a significant cause of worldwide disability, illness and mortality (Health Effects Institute 2020, 2022). Global particulate concentrations (PM2.5) peaked between 2010 and 2015 and have since declined modestly – driven by steep decreases in China and gradual declines in south Asia, Europe and the US – but they remain above levels prevailing in the 1990s (Chart 20).

Chart 20: Global air particulate concentrations, 1998-2023



Source: Greenstone et al., 2025

However, in some areas where air quality had previously improved, e.g. the US and Canada, the growing frequency and scale of wildfires in recent years has been reversing that trend, with wildfire smoke becoming a major source of pollution that is raising overall air pollution levels (Greenstone *et al.*, 2025). In 2023, particulate (PM 2.5) levels rose by 50% in Canada and 20% in the US due to wildfire smoke (Greenstone *et al.*, 2025).

In Canada, the extensive 2023 wildfires drove particulate pollution levels above the national annual PM2.5 standard of 8.8 µg/m³ for the first time since 1998, with more than 50% of

Canadians breathing air exceeding the standard, compared to less than 5% over the previous five years (Greenstone *et al.*, 2025).

Only one percent of the global population is estimated to breathe clean air according to World Health Organization (WHO) standards (Damania *et al.*, 2025). Rates of population exposure to hazardous levels of outdoor air pollutants are highest in India, China, west Africa and eastern Europe.

Water pollution has worsened significantly over time in many parts of the world, with direct impacts on the health of humans, fish, aquatic birds, marine mammals and freshwater and marine ecosystems. Globally, an estimated 80% of industrial and municipal wastewater is discharged into the environment untreated; this proportion is higher in the least developed countries (Lin *et al.*, 2022). Each year over 300 million tons of industrial wastes are dumped into water worldwide, including heavy metals, solvents and toxic sludge (IPBES, 2019). Fertilizers entering coastal waters have produced more than 400 ocean dead zones totalling an area of over 245,000 square kilometres (IPBES, 2019). And significant quantities of military waste, including war ships and planes, chemical munitions and unexploded ordnance have been disposed of in the oceans, some corroding and leaching toxic chemicals (Helsinki Commission, 2024).[25]

In Latin America, Africa and Asia, water pollution has worsened since the 1990s in the majority of rivers (UNEP, 2016). Severe pathogen pollution, including high concentrations of coliform bacteria, is found in approximately on third of these rivers (UNEP, 2016). The major underlying causes of this growing water pollution have been identified as: population growth, increased economic activity, intensification and expansion of agriculture, and increased discharge of untreated or inadequately treated sewage (UNEP, 2016).

In Europe, nearly half of surface water bodies failed EU quality standards in 2021; only 37% of surface water bodies achieved ‘good’ or ‘high’ ecological status, and only 29% achieved ‘good’ chemical status (European Environment Agency, 2025). Europe’s waters were found to be severely impacted by chemicals, predominantly from air pollution from coal-powered energy generation and pollution by nutrients and pesticides from agriculture (EEA, 2025).

In the United States, it was found that in 2022 51% of assessed river miles, 55% of lake acres and 26% of estuary miles were too polluted to meet quality standards for swimming, recreation, aquatic life, fish consumption or as drinking water sources (Kelderman *et al.*, 2022).

Only a small and declining proportion of the world population now draws drinking water directly from freshwater sources, as water in most rivers and lakes is no longer clean enough to drink (IPBES, 2020).

Plastic pollution is an issue of particular concern. Annual global plastic production has risen steadily, reaching 414 million tonnes by 2023 (Statista, 2025). Cumulative global plastic production since 1950 exceeds 11 billion tons; three quarters of this has become plastic waste,

[25] The Baltic Sea alone is the repository for some 40,000 tonnes of chemical munitions and an estimated 500,000 tonnes of conventional munitions dumped after WWII (Helsinki Commission, 2024).

the majority of which has been neither recycled (10%) nor incinerated (14%) but has entered landfills or the environment, including the oceans (Statista, 2025; UNEP, 2021). Unmanaged global plastic waste emitted into the environment had risen to an estimated 52 million metric tonnes per year by 2020 (Cottom *et al.*, 2024). The global weight of accumulated plastics exceeded that of total human biomass by 1962 and that of total animal biomass by 1994; and in some earth systems the quantity of plastics now rivals that of natural organic carbon (Stubbins *et al.*, 2021).[26]

Marine and ocean plastic pollution has increased tenfold since 1980 (IPBES, 2019) and is now described as the "largest, most harmful and most persistent" component of marine litter, estimated at between 75 million and 199 million tons and accounting for at least 85% of marine waste (UNEP, 2021).[27] By 2016, 9-14 million tons of plastic were entering aquatic ecosystems annually (UNEP, 2021). Most plastic does not biodegrade but simply breaks down into smaller microparticles and nanoparticles that enter the food chains of wildlife and humans.

Persistent organic pollutants (POPs) are another product class of particular concern, known to include many carcinogenic and toxic elements. It includes chemicals such as pesticides (e.g. DDT), PCBs, flame retardants and "forever chemicals", or PFASs, such as stain repellents and non-stick pan coatings, as well as manufacturing byproducts such as dioxin (Fry & Power, 2017) This class of chemicals is highly persistent in the environment as it resists degradation, and often bioaccumulates. Tens of millions of tonnes of these chemicals have been produced (Li *et al.*, 2023). A recent review of just 25 of these POPs indicated that as of 2020, a cumulative total of 31 million tonnes had been produced, of which 20 million tonnes had been released into the environment (Li *et al.*, 2023). POPs have been detected worldwide in contaminated air, water and soil, as well as in human and animal tissues, despite their known toxicity and adverse health impacts.

Soil contamination affects large areas of land globally, reducing the available stock of arable land and negatively affecting crop yields, as well as posing environmental and health risks (FAO, 2015a). It can be caused by industrial activity, mining, fossil fuel extraction, inappropriate waste disposal, transportation or nuclear accidents, military activity, air pollution, agricultural chemicals, floods or irrigation with contaminated groundwater (FAO, 2015a). For sites that are no longer in operation and where the original owner is insolvent or unreachable, this often produces a public sector financial liability, sometimes with long-term management requirements.

In China, one fifth of all farmland is estimated to be contaminated by heavy metals, largely due to air pollution (FAO, 2015a). In Europe, 3 million potentially contaminated sites have been identified, largely related to waste disposal and industrial activity; only a small minority (15%) of high-risk sites have been successfully remediated. Canada has an inventory of federally managed contaminated sites, most including contaminated soil, sediment and/or groundwater,

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[26] The magnitude of global plastic accumulation has led some scientists to describe it as an emergent component of the Earth's carbon cycle (Stubbins et al., 2021).

[27] More than half the plastics found floating in some ocean gyres were produced in the 1990s and earlier (UNEP, 2021).

of which over 4,400 have not yet been remediated and a further 1,400 not yet assessed, representing a financial liability of $10 billion (Commissioner of the Environment and Sustainable Development, 2024; Treasury Board, 2025). [28] In Alberta, there are currently 170,000 abandoned oil and gas wells, all of which must be properly closed and decommissioned to ensure that they do not pose environmental and health risks (Alberta Energy Regulator, 2025). Total assessed decommissioning costs for inactive wells range from $260 -$282 billion, including oil sands and tailings decommissioning, equivalent to over 70% of 2025 Alberta GDP (Jones, 2025). Over 3,000 of these are 'orphan wells', meaning that there is no solvent owner; the cost of cleanup of these wells was assessed in 2025 at $1.1 billion (Orphan Well Association, 2025).

In the US, the Environmental Protection Agency (EPA) has identified 120,000 sites considered likely to have handled or released PFAS, and the US Geological Survey estimates that 45% of US tap water contains these toxic "forever chemicals" (Brind'Amour, 2024). In addition, there are approximately 500,000 abandoned mines in the US, which are estimated to have contaminated 40% of US rivers and 50% of all lakes (GAO, 2023). Older mines, in particular, have generated "large quantities of hazardous substances, often over hundreds of square miles" (GAO, 2023), contributing to a total federal government environmental liability assessed at $666 billion in 2024 (US Treasury, 2024).

Since the advent of the nuclear era in the 1940s, radioactive nuclear waste has been generated by nuclear weapons; power reactors; reactors for research and isotope generation; and propulsion reactors, such as those used in submarines. Radioactive contamination from nuclear sources is severe in some parts of the world, resulting in arable and inhabited land being taken out of production for very long periods. The Chernobyl disaster resulted in the creation of a quasi-permanent exclusion zone of 2,600 square kilometres; while the 2011 explosion of the Fukushima nuclear power plant following a tsunami resulted in soil contamination of an area of 800 square kilometres (FAO, 2015a). Similarly, nuclear testing in the Marshall Islands in the 1940s and 1950s resulted in serious long-term soil contamination, with access to several islands still restricted and the expectation that some areas will be contaminated effectively forever (FAO, 2015a).

The nuclear-armed states have conducted over 2,000 nuclear weapons tests, of which one quarter were atmospheric or underwater tests, resulting in dispersal of radioactive material, which has been linked to significant health impacts (Pravalie, 2014).

As of 2016, 448 nuclear power reactors were being operated in 30 countries, generating about 10% of global electricity (IAEA, 2022). A further 141 reactors had been shut down, of which only 20 had been fully dismantled. These reactors had generated 38 million square metres of solid

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[28] These sites include landfills, abandoned mines, military bases and airports. Among the abandoned mines is the former Giant gold mine 5 kilometres from Yellowknife, NWT, which contains 237,000 tonnes of arsenic; and the former Faro open-pit lead-zinc mine in the Yukon, which contains 70 million tonnes of tailings and 139 million cubic metres of contaminated water. Cleanup costs for these sites were assessed in 2022 at $4.4 billion and $1 billion, respectively (CIRNAC, 2022). The Giant mine cleanup cost exceeds NWT GDP. Some sites (including these two mines) require perpetual care and monitoring to ensure that contamination remains contained (Commissioner of the Environment and Sustainable Development, 2024).

radioactive waste and 122 million square metres of liquid radioactive waste (IAEA, 2022). Approximately half of the liquid waste was awaiting processing, while half had been disposed of by injection into deep wells (IAEA, 2022).

High-level waste accounts for only a small percentage of all radioactive waste, but is of particular concern as it produces fatal radiation doses during short periods of direct exposure, and may enter food chains if it goes into groundwater or rivers (USNRC, 2024). The half-life of radioactive isotopes contained in high-level waste ranges from 30 years for strontium and cesium, to 24,000 years for plutonium, posing a long-term containment and management challenge, particularly in light of ongoing climate change and associated increases in flooding risk and sea levels (USNRC, 2024).

Synergies

It has been widely observed that the three major types of environmental damage – climate change, biodiversity loss, and waste and pollution – are closely interrelated and often reinforce and amplify each other. For example, climate change contributes significantly to loss of biodiversity, while loss of biodiversity – e.g. deforestation – can in turn accelerate climate change. Greenhouse gas pollution is the key driver of climate change, while other types of pollution contribute to wildlife deaths and species loss. Accelerating wildfire incidence due to climate change produces significant smoke pollution. Some of these synergistic effects have been acting to reduce the effectiveness of land and marine carbon sinks, which currently absorb about half of man-made carbon emissions (Breckenfelder *et al.*, 2023; Friedlingstein *et al.*, 2025b).

- The UNEP has described climate change, biodiversity loss and pollution and waste as a triple crisis, with the current model of natural resource use driving an "unprecedented planetary crisis of climate change, biodiversity loss and pollution." (UNEP, 2024a).
- The IPBES has stated: "The climate crisis cannot be addressed in isolation. It is inseparable from biodiversity loss, water scarcity, food insecurity and pollution." (McElwee *et al*., 2025)
- Sixty-five scientists affiliated with the Leibniz Research Network on Biodiversity affirmed that: "Biodiversity loss and climate change are one indivisible crisis now so severe as to be a global health emergency – the loss of biodiversity threatens the full range of life-supporting services provided by ecosystems." (Thonicke *et al.*, 2024).
- Johan Rockstrom, a lead scientist in the Planetary Boundaries project, stated: "In the midst of the climate crisis, we are undermining the capacity of the living biosphere to buffer the strain caused by the GHG driven global energy imbalance." (Rockstrom, 2024).
- Stenzel *et al.* stated: "The current major crisis of the coupled climate-biosphere system threatens both the ability of global ecosystems to function and co-regulate Earth's state, and nature's contributions to people." (Stenzel *et al.*, 2025).

The key implication of these statements is that each of these types of natural capital depletion need to be addressed in an integrated manner rather than in isolation.

5. Declining Measurements of Natural Capital

Natural capital measurements are based on scientific assessments. However, efforts to measure natural capital as part of an economic framework are much more recent, and far less developed and comprehensive than the scientific assessments on which they are based – largely because the underlying methodology is still evolving. Accordingly, in any comparison of natural capital measurements and scientific assessments of the environment, the latter should be viewed as more definitive. Indeed, a key test of the reliability of any measure of natural capital should be the degree to which it aligns with the weight of the scientific evidence.

The term "natural capital" was introduced by Schumacher in the 1970s, who asserted that natural capital stocks account for the larger part of all capital (Schumacher, 1973). Concerted attempts to measure natural capital have been undertaken over the past dozen or so years by the United Nations Environment Program (UNEP), the World Bank and the OECD, due to growing recognition of its relevance to economic outcomes.[29] These measures initially included only the value of stocks of marketable natural resources, such as timber and mineral reserves but their scope has progressively expanded over time to include a number of ecosystem services; nevertheless, all measures but should still be viewed as quite incomplete, as data availability and methodological approaches continue to evolve.

Detailed multinational natural capital measurements have been produced to date by the United Nations Environment Program (UNEP) and the World Bank, with differing inclusions and methodologies. The OECD has also produced natural capital estimates, based largely on World Bank data, as part of its work to develop environmentally adjusted productivity figures. As these sets of global measures are based on aggregations of national data, none includes values for natural systems and assets outside national boundaries, such as Antarctica, the atmosphere or open oceans. Many other ecosystem services are also excluded, including, for example, the value of megafauna as carbon sinks; and kelp forests and seagrass meadows as fish habitat, carbon sinks and coastal protection.

United Nations Environment Program Measures

The UNEP measures are the most comprehensive. Since 2012, the United Nations Environment Program (UNEP) has produced four iterations of its inclusive wealth index, 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 inclusive wealth index, released in 2023, assesses these measures of capital for 163 countries covering 98% of global population over the years 1992-2019 and also produces aggregate global measures (Chart 5). Natural capital is defined by the UNEP to include: 1) three renewable resources, fisheries, forests and agricultural

[29] Another motivating factor in the development of wealth indicators was the desire to develop measures other than GDP as indicators of living standards and well-being, or to move "beyond GDP". The notion that assets, a stock, are a useful complement to measures of annual output, a flow and essentially a measure of "throughput", was one of the motivations for the development of indicators such as the UNEP Inclusive Wealth measures.

land; 2) fourteen nonrenewable resources, including three fossil fuels and eleven minerals; and 3) market and non-market values for some ecosystems (UNEP, 2023c). Specifically, it includes: fossil fuels (oil, natural gas, coal); minerals (bauxite, nickel, copper, phosphate, gold, silver, iron, tin, lead and zinc); forest resources (timber and non-timber forest); agricultural land (cropland and pastureland); and fisheries. A number of ecosystem services are included in these measures. Total capital is also adjusted for carbon damages, including blue carbon accounting.

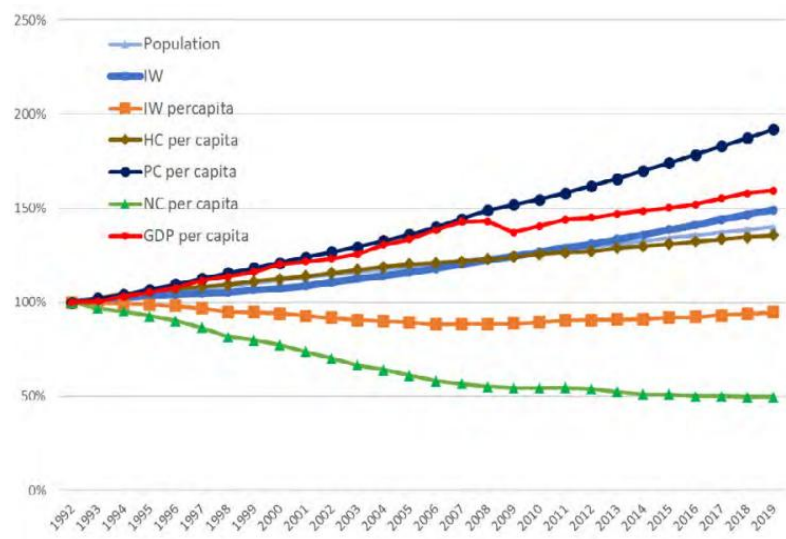
The value of natural assets is defined by the UNEP as the present discounted value of the future net benefits that can be expected over the life of the resource, based on a discount rate of 5%. Thus, the assessed value of forests, for example, goes well beyond timber values and also includes the value 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 (UNU-IHDP and UNEP, 2014). 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 (UNU-IHDP and UNEP, 2014). 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 used. 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 these calculations (Tol, 2023). Lower discount rates reduce the amount by which future costs are discounted, and therefore act to raise assessments of these costs.

The scope of the UNEP definitions of natural capital and total capital has broadened over successive iterations of the index. The latest version of the index includes blue carbon accounting in its carbon damage adjustment for the first time (UNEP, 2023c). However, many ecosystem services are not yet included, as comparable national data is not yet available (UNEP, 2023c). Therefore, current measures of natural capital still need to be viewed as a work in progress.

Nevertheless, the UNEP findings are striking. Chart 21 shows that while produced capital (PC) per person nearly doubled globally over the 1992-2019 period (a 92% increase) and human capital (HC) per capita grew by 38%, natural capital (NC) per capita declined by 50% . The steep drop in natural capital per capita reflected both a 28% absolute decrease in total natural capital and global population growth of 41% over this period. Declines occurred for both renewable and nonrenewable forms of natural capital, with renewables declining slightly faster. Natural capital per capita fell in 151 of the 163 countries assessed.

The worldwide decline in natural capital was sufficiently large to depress the per capita volume of total global capital, referred to by the UN as Inclusive Wealth (IW). By 2019, total global capital, or IW, per capita, was 5% below its 1992 value.

Chart 21. Changes in natural, human, produced and total capital (IW) per capita and other indicators, 1992-2019



Source: UNEP (2023c)

The UNEP findings on natural capital declines align with the IPBES findings that fourteen of eighteen contributions of nature – or ecosystem services – have declined over the past fifty years, and also with other scientific evidence presented in the previous section.

Any decline in productive capital generally reduces productive capacity and hence productivity. A 50% per capita decline in natural capital would therefore be expected to have a significant negative impact on productivity growth. Because the decline in natural capital has been sufficiently large as to reduce the world's *total* stock of productive capital, the productivity impact should be even more pronounced.

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 these declines. All 15 of these countries were located in Africa and South America.

Clearly, the impact of natural capital declines on total capital will be dependent on the relative shares of the three different types of capital – which change over time in accordance with differing rates of growth or decline. In 2019, those relative shares, as a percentage of total capital, were:

- Human capital – 54%
- Produced capital – 28%
- Natural capital – 18%

Even with this modest assessed share of total capital, however, based on still evolving measures of natural capital, depletion of natural capital depressed the stock of total productive capital per capita.

A further striking finding shown in the chart is the widening divergence between global growth of GDP per capita and produced capital per capita. GDP per capita growth slowed relative to that of produced capital, and no longer keeps pace with growth of produced capital per capita. The clear implication is that the productivity returns to investments in produced capital have declined over time – possibly because natural capital declines have also depressed the total stock of productive capital per capita.

It would be highly surprising if a 50% per capita decline in any form of productive capital did not materially reduce productivity growth. When the decline is sufficiently large as to also reduce the *total* available amount of productive capital – a measure of the total productive capacity of global economies – it would be astonishing if there was no negative impact on aggregate productivity.

World Bank Measures

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, 2024b). Its measures of natural capital are less comprehensive than those of the UNEP and account for a much smaller share of total capital than those of the UNEP – 8% of total capital in 2020, compared with 18% in 2019 in the UNEP measure.[30] In addition, the World Bank measures explicitly treat renewable and nonrenewable natural capital as separate asset classes. Renewable natural capital (6% 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% of total capital in 2020) includes fossil fuels (oil, natural gas and coal) and thirteen metals and minerals.

The relative shares of the major capital classes in the World Bank accounts in 2020 as a percentage of total capital were:

- Human capital – 60%
- Produced capital – 32%
- Natural capital – 8%

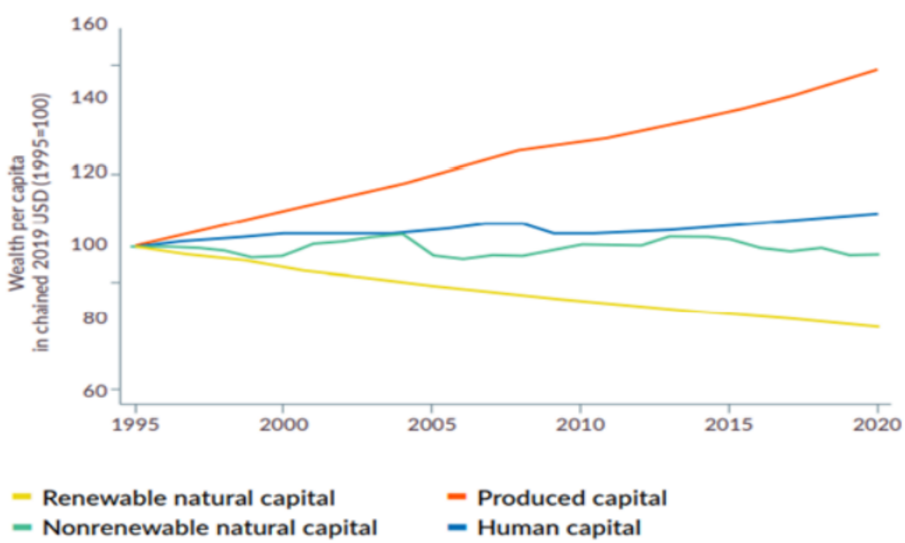
Asset valuation is based on a calculation of discounted sum of net benefits over a time period, where net benefits are defined as resource rents, i.e. total revenues minus total cost of production (World Bank, 2021b). The discount rate used in net present value calculations is 4%, which (like the 5% rate used by the UNEP) is higher than that employed by some analysts and institutions. For example, the US Environmental Protection Agency recently used a 2% rate as its central discount rate in calculating the social cost of carbon (US EPA, 2023). Higher discount rates will, ceteris paribus, act to reduce the value of future ecosystem services and therefore the assessed value of natural capital.

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

A key methodological difference between the World Bank and UNEP approaches is the World Bank's use of observed market prices or proxies to value capital, while the UNEP relies more on shadow prices.

The World Bank, like the UNEP, finds significant declines in global natural capital per capita over the assessed time period. Chart 22 shows the World Bank assessments that between 1995 and 2020, on a per capita basis: global produced capital rose by 47%; human capital rose by 9%; nonrenewable natural capital declined by 2.5%; and renewable natural capital declined by over 20%.[31] However, while the UNEP declines in natural capital per capita were driven by both absolute declines in the value of natural capital and by population growth, the World Bank declines were driven entirely by population growth, with a 5% increase in measured natural capital globally over the 1995-2020 period. The absence of absolute declines in the value of natural capital in the World Bank measures is clearly misaligned with IPBES and other scientific findings of significant ecosystem and biodiversity declines in recent decades.

Chart 22: World Bank measures of global capital per capita, by asset category, 1995–2020
1995 = 100



Source: World Bank (2024)

The Bank acknowledges 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%. 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,

[31] 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.

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 per capita in both the UNEP and World Bank wealth measures are highly significant, as they represent growing production constraints in the global economy.

Achieving growth by running down any stock of productive capital is clearly not a sustainable or desirable pathway.

Other measures

At the more micro level, a number of pathbreaking initiatives have been undertaken to assess the dollar value of ecosystem services, including carbon services, provided by animals and plants as varied as whales, elephants, tigers, sea otters, beavers, bison, phytoplankton and seagrass meadows (Berzaghi *et al.*, 2022; Chami *et al.*, 2019; Chami, 2025). This research usually emphasizes that in many cases the value of ecosystem services provided exceeds the value of the plant or animal as a marketed commodity (Text Box 5). Many of these measures have not yet been incorporated into the UNEP or World Bank natural capital measures, and therefore represent areas for future work by these organizations.

6. Insights from the Literature

The landmark UK report, *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 and are generally not included in GDP. He observes that expanded demand for provisioning goods has often directly diminished nature's ability to supply environmental maintenance and regulating services (Dasgupta & Levin, 2023).

This distinction is highly relevant to natural capital measures, as these measurements have generally been undertaken first and most extensively for provisioning goods; and to a much lesser extent for ecosystem services, which scientific evidence has shown are declining most rapidly. They are therefore likely to understate the degree of decline in natural capital.

Dasgupta notes further that the longstanding 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 & Levin, 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 & Levin, 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.*, for example, found that natural capital erosion can result in impaired human capital development; 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 (Damania *et al.*, 2023).

Gardes-Landolfini *et al.* 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 (Gardes-Landolfini *et al.*, 2024). 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; Olewiler, 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 report. Many commentators have therefore recommended that natural capital be accounted for separately as a factor of production, as its absence can cause important determinants of long-term growth to be overlooked (Brandt *et al.*, 2013; Dasgupta, 2021; Meadows *et al.*, 1972; Nordhaus, 1974; Olewiler, 2002).

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 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);[32]

• Expenditures to improve environmental outcomes, as positive adjustments to output: (i.e. GVA + environmental expenditures = PK + L + MFP).

The OECD has undertaken work since 2011 to develop environmentally-adjusted measures of multifactor productivity (EAMFP) that incorporate two of these variables by accounting 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). Specifically, it includes the following, assessed using OECD and World Bank data:

[32] Pollution could, in principle, alternatively be used to adjust natural capital measures as it acts to reduce their asset value.

- Fossil fuels: hard coal, brown coal, crude oil, natural gas
- Mineral resources; bauxite, copper, gold, iron ore, lead, nickel, phosphate, silver, tin, zinc
- Land resources: cropland, pastureland, forestland
- Biological resources: marine capture fisheries, non-cultivated timber
- Ecosystem services: watershed protection by forests, non-wood forest products, coastal flooding protection by mangroves
- Renewable energy resources: hydro, wind, solar

The OECD acknowledges that this definition of natural capital still excludes many resources (e.g. freshwater, soil, sand, limestone, lithium, cobalt and rare earth minerals) and many foundational ecosystem services (e.g. carbon storage, pollination, water and air purification, habitat protection). Accordingly, its natural capital measure remains a very incomplete one that is heavily weighted towards direct harvesting of resources ('provisioning services', providing an immediate and tangible economic benefit) as opposed to regulating ecosystem services, required for long-term sustainability. The OECD's pollution abatement measure accounts for emissions of five greenhouse gases and seven other air pollutants. It does not include water or soil pollution.

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 report. In contrast, the OECD found that labour and produced capital contributed positively to national economic growth in nearly every instance.[33] 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.

Hua and Wang undertake a similar exercise. They integrate natural capital and pollutant emissions into the expanded growth accounting framework established by Brandt *et al.* in order to measure an environmentally adjusted MFP for 51 OECD and G20 countries between 1990 and 2020, using World Bank data on natural capital and the following formulation:

GDP growth – Adjustment for pollution abatement = Growth contribution of human capital + growth contribution of produced capital +Growth contribution of natural capital + Environmentally adjusted multifactor productivity growth (EAMFP)

They found that MFP is higher than EAMFP in 40 out of 51 countries, inferring that traditional productivity growth measures overestimate both actual productivity growth and the quality of economic development, hindering adjustment towards sustainability (Hua & Wang, 2023).

[33] 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.

7. Impacts of Declining Natural Capital on Productivity

Transmission channels

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 evacuations and business closures because of wildfire smoke or extreme weather.

• *Labour intensity and input*. Adverse events such as hurricanes, 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, reducing the lifespan of productive capital; they can also affect MFP by inducing capital / labour mismatch. Repair and replacement costs divert resources from productive new investments.

• *Human capita*l. Illness, disability and premature mortality – due to, for example, air pollution or extreme weather events – reduce lifetime worker output and also the return on investments in skills and education and other human capital development.

• *Obsolescence*. Unanticipated environmental changes can result in accelerated obsolescence, accelerating depreciation and reducing the productive lifespan of investments. Adaptations and purchases of more resilient or climate-appropriate equipment and infrastructure can be expensive, raising production costs and displacing scarce investment dollars.

• *Dynamic impacts*. Natural capital declines can affect productivity through their impact on variables such as business viability, investment, 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).

• *Financial markets.* Negative shocks can be amplified via changes in asset valuations, the supply of credit, and insurance markets. They can reduce equity values; depreciate loan collateral; increase defaults; raise insurance costs or limit insurability altogether; and disrupt operations of financial institutions.

• *Supply chains.* Negative shocks can be propagated throughout economies to other regions, countries or sectors via supply chains.

• *Uncertainty.* Diminished environmental stability can lead to uncertainty re the future, reducing willingness to invest.

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 and compounding impacts as well as immediate ones. 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. Uninsured losses – the majority of all losses globally – may suffer from particular delays (Swiss Re, 2024a). Delayed rebuilding and diversion of investment dollars results in a lower baseline of capital stock on which to build future growth, with compounding effects over time.

There is a rapidly burgeoning literature on the productivity impacts of various types of natural capital erosion in specific sectors and countries, particularly around the impacts of climate change. These productivity impacts have generally not been incorporated into national productivity accounts because efforts to integrate measurements of natural capital into national economic accounts are still in the early developmental stages. Accordingly, at the national macroeconomic level, these productivity impacts would typically be attributed to physical or human capital, or to multifactor productivity.

The next four sections examine the impacts of natural capital depletion on productivity growth and the transmission channels for these impacts in four key areas: a) climate change; b) biodiversity and nature loss; c) soil and subsoil resource depletion; and d) pollution and waste.

a) Productivity impacts: climate change

There is a rapidly growing literature on the productivity impacts of climate change, described by Nicholas Stern as "the greatest externality the world has ever seen" (Stern, 2006).

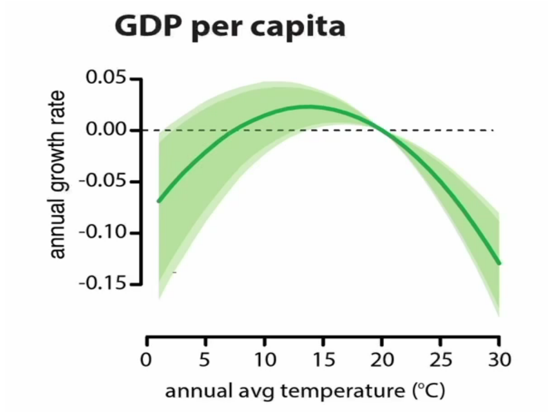
Macroeconomic impacts

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 evidence is now virtually incontrovertible that climate change to date has already had a significant negative impact on productivity and GDP growth, both nationally and global level.

Burke *et al.* showed that a strong relationship has existed worldwide since 1960 between average national annual temperatures and productivity, with GDP per capita growth markedly lower at average temperatures above 13.6° C (Burke, Hsiang and Miguel, 2015b). 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). Above an annual average of 20°C, productivity growth becomes negative (Chart 23). The researchers did not find any evidence of adaptation, i.e. reduced economic responsiveness of productivity to temperature, over the timeframe examined, 1961-2020 (Hsiang, 2025).

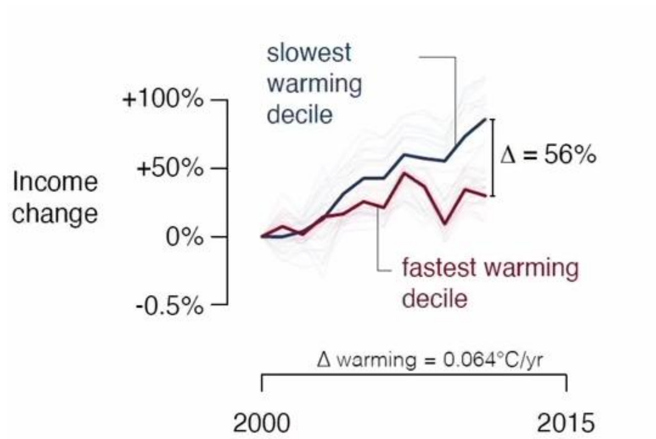
Chart 23: Global response of growth to temperature



Source: Burke, Hsiang and Miguel (2015b); Hsiang (2025)

Researchers have also found a strong inverse relationship between the rate of warming within countries and the rate of income growth. In India, a widening gap emerged between 2000 and 2015 between income growth in the fastest and slowest warming regions of the country; cumulative income growth in the slowest warming regional decile was 56% higher than that in the fastest warming decile by the end of the period assessed (Chart 24). This pattern was also found in other countries, including Indonesia and Brazil (Hsiang, 2025).

Chart 24: Rate of warming by decile and associated rate of income change in India, 2000-2015



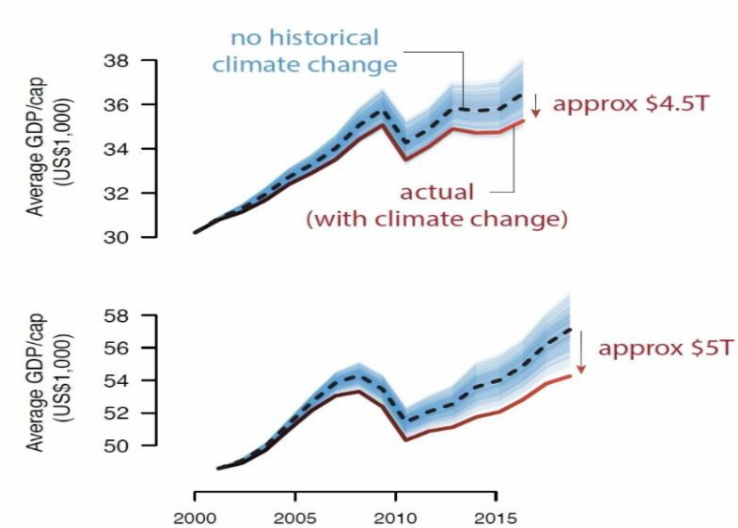
Source: Hsiang (2025); Burke & Tanutama (2019)

When actual growth in income per capita in the United States and Europe was compared to estimated growth without climate change, it was found that climate change between 2000 and 2024 had acted to depress income by a cumulative total of $US 4.5 trillion in Europe and $5US trillion in the U.S. (Chart 25).[34]

[34] This represents a cumulative loss of approximately 1.2% of US GDP between 2000 and 2024.

Hsiang estimates that cumulative global economic damage to date from climate change is approximately $US 50 trillion in foregone income (Hsiang, 2025).

Chart 25: Income lost due to warming since 2000



Europe

United States

Source: Burke and Tanutama (2019); Hsiang (2025)

Bilal and Kanzig 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 (Bilal and Kanzig, 2024).[35] 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% on impact and 10% within four years, with declines persistent over the ten years assessed. World GDP fell by 2% on impact, by 12% within six years, and by 20% in the long term. 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 annual world GDP per capita by 15% by 2019 compared to the counterfactual steady state climate. 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

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

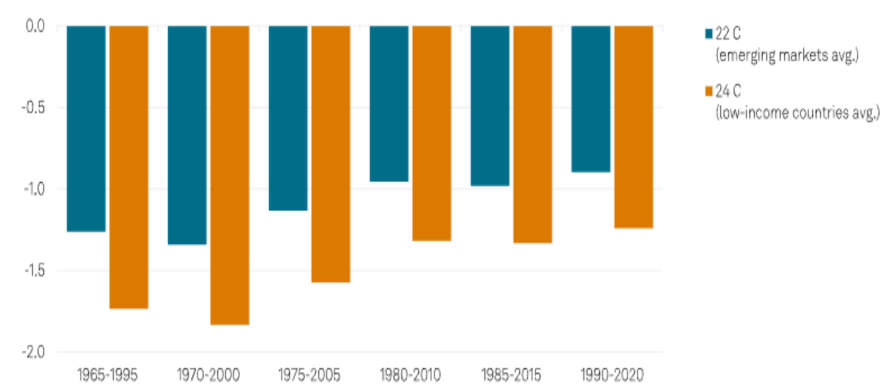
climate change has resulted in its effects being obscured behind background economic variability.

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, with respect to extreme temperature, wind and precipitation. This is consistent with the geoscience literature that extreme wind and precipitation are outcomes of global rather than local temperature variations, including ocean temperatures.

Sawyer *et al.* assessed the impacts of climate change since 2015 on the Canadian economy by integrating bottom-up analyses of climate impacts on impact groups into a macroeconomic model of the Canadian economy (Sawyer *et al.*, 2022). They found that climate change since 2015 is already resulting in large and rising annual GDP losses, amounting to 1% of GDP by 2025, effectively nearly eradicating projected 2025 GDP growth. Manufacturing sector output was reduced by 1% by 2025, while service sector output was 1.4% lower. The most important channels of impact were weather disasters, heat impacts on labour productivity, flooding and premature death.

Amiot and Thompson found pronounced impacts from a 1°C temperature increase on real GDP per capita growth in national economies (Amiot & Thompson, 2025). For emerging market economies (annual average temperature 22°C) the increase reduced real GDP per capita growth by 1. 2-1.3 percentage points annually between 1965 and 2000, with impacts gradually declining over time, to a 0.9 percentage point annual reduction between 1990 and 2020 (Chart 26). For low-income countries (annual average temperature 24°C), the impact was even more pronounced – an annual growth rate reduction of 1.7-1.8 percentage points between 1965 and 2000, declining to a reduction of 1.2 percentage points between 1990 and 2020. The authors attribute this decreasing sensitivity of economic activity to rising temperatures – a finding that differs from that of Hsiang – primarily to adaptation, with the declining share of agriculture in GDP also playing a role.

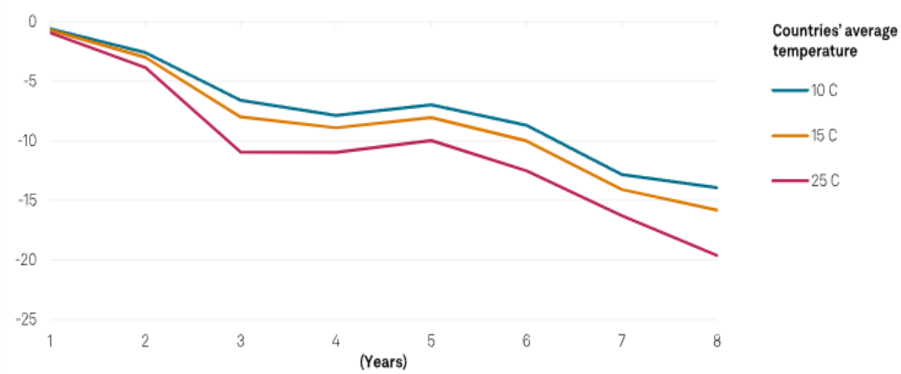
Chart 26: Effect of a 1°C annual average temperature rise on annual real GDP per capita growth (% point change)



Source: Amiot & Thompson (2025)

Amiot and Thompson also assessed the cumulative GDP per capita loss over eight years after a 1C temperature rise, for countries with different average annual temperatures, finding the strongest impact in the warmest countries. They found the greatest cumulative GDP declines, nearly 20% after eight years, for countries with average temperatures of 25°C (Chart 27). For countries with average temperatures of 20°C, the cumulative eight-year decline was 16%; while for those with average temperatures of 15°C, it was 14%.

Chart 27: Cumulative GDP per capita loss after 1°C temperature rise (%), by countries' average temperature



Source: Amiot & Thompson (2025)

One important component of climate change has been rapidly accelerating soil aridification and desertification as temperatures have risen and precipitation patterns have changed, with Africa and Asia the most severely affected continents. Malpede and Percoco assessed the economic effects of climate-induced soil aridification between 1990 and 2015 (Malpede and Percoco, 2021). They concluded that during this period, aridification reduced the average GDP per capita by 12% in African countries and by 3% in Asian countries.

Water scarcity also acts directly to constrain real GDP growth, via its effect on productivity. An analysis of 169 countries from 1965-2020 found that water scarcity has a negative and statistically significant association with growth. Each percentage point of water scarcity is associated with 0.08 to 0.10 percentage points lower economic growth (Frost *et al.*, 2025).

The majority of published 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. Given that material global warming has already occurred, it is implausible that warming to date has not affected economic growth, although evidence suggests that impacts are accelerating with incremental temperature increases.

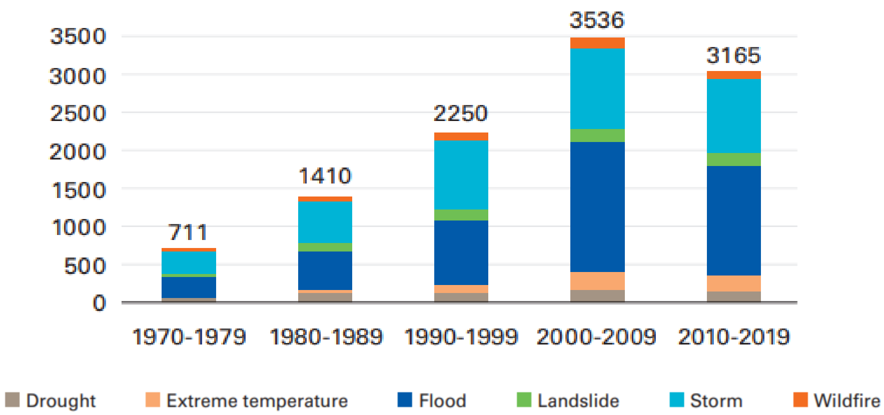
Extreme weather events

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.

The World Meteorological Organization found that between 1970 and 2019 there were 11,072 disasters globally attributed to weather, climate or water hazards, resulting in 2.1 million deaths and $US 3.64T in property damage losses (WMO, 2021).[36] Property damage costs, which do not include lost output, averaged 0.2% to 0.3% of annual global GDP during this period.

Extreme weather 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 not included in most Integrated Assessment Models (Newman and Noy, 2023).[37] Globally, they have increased steeply 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 28). These increases have been clearly linked to human-induced climate change (IPCC, 2021; WMO, 2021). Between 2015 and 2017, 62 of 77 extreme weather events showed a significant link to human influence, including virtually all extreme heatwaves (WMO, 2021).

Chart 28: Global number of reported weather and climate-related disasters, by decade, 1970-2019



Source: WMO (2021)

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 29). 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, 2024a).

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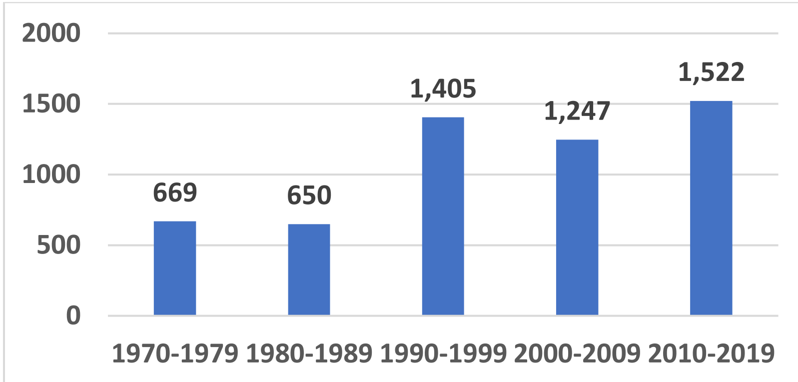
[36] The data used by the WMO originated from the Emergency Events Database (EM-DAT), managed by the Centre for Research on the Epidemiology of Disasters (CRED) at the Université Catholique de Louvain.

[37] Integrated Assessment Models (IAMs) are models that incorporate both scientific and economic data in order to evaluate the nature and magnitude of environment-economy interactions.

Chart 29: Reported global economic losses from weather and climate-related disasters, by decade* (billions of 2017 USD)

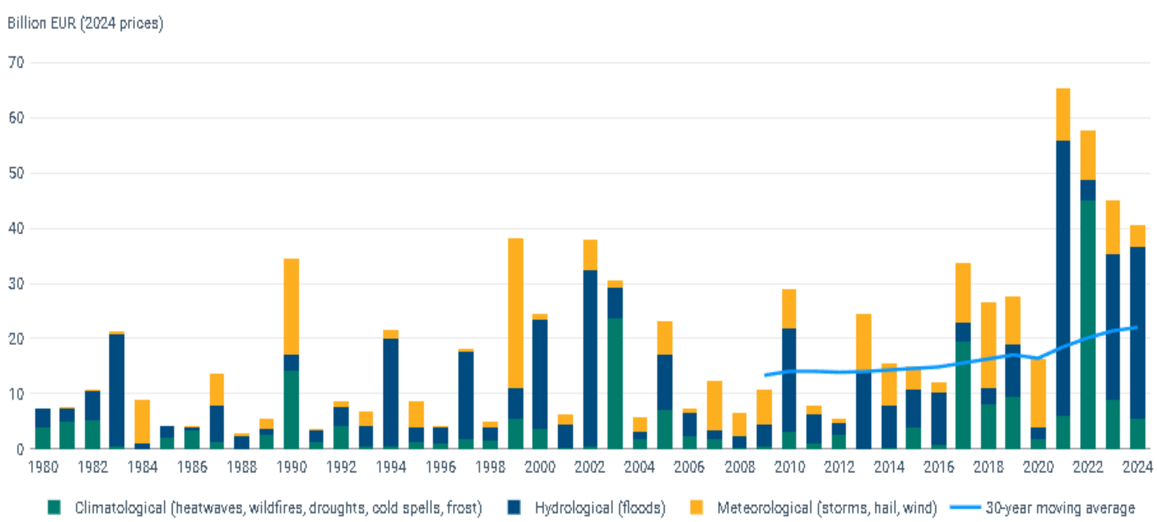


**These include droughts, extreme temperatures, floods, landslides, storms and wildfires.*
Source: WMO (2023), author's calculations.

Global costs and fatalities from extreme events have remained high since 2019. In 2024, natural hazard disasters – 90% climate and weather-related – affected 167 million people, directly causing 16,753 fatalities and resulting in damage costs of $US242 billion (UCLouvain/CRED, 2025).

EU and US data also show a strong continuation of the rising trend. In the EU27, average annual economic losses (i.e. property damage) due to weather and climate-related extreme events rose from 2024 EUR 9 billion in the 1980s to 20 billion in the 2010s and 45 billion in the 2020-2024 period (Chart 30). Damages exceeded 2024 EUR 40 billion in every year after 2020. Total cumulative losses from 1980-2024 were 2024 EUR 822 billion, of which only 20% were insured; cumulative per capita losses were highest in Slovenia, at EUR 9,176. A total of 441,069 fatalities in EU member nations were directly ascribed to these events between 1980 and 2024.

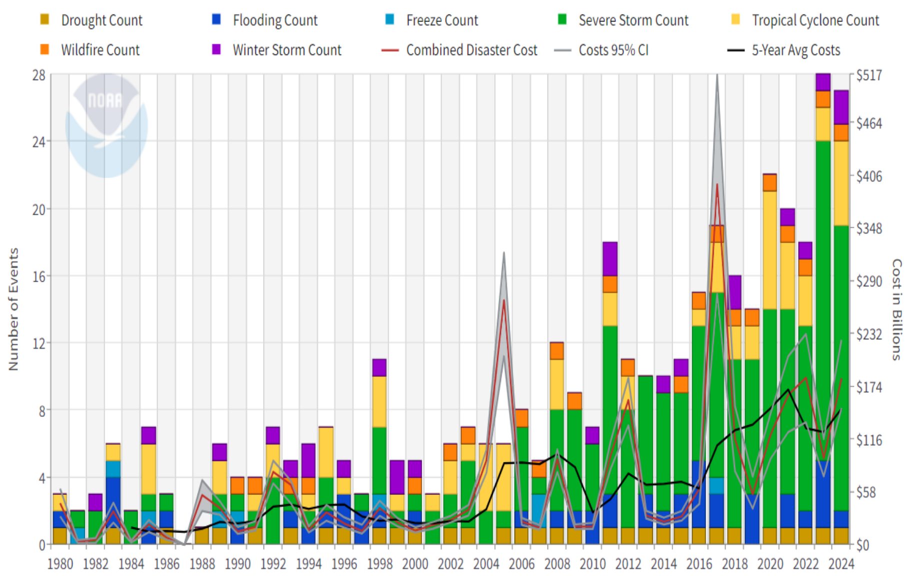
Chart 30: Annual economic losses caused by weather-and climate-related extreme events in EU member states, 1980-2024 (Billions of 2024 Euros)



Source: European Environment Agency (2025)

In the US, there have been 417 weather and climate disasters with property damages of $1 B or more since 1980, producing cumulative damages of 2024$US 3.1 trillion, or over 2024 $9,000 per person (Chart 31) (NOAA, 2024, 2025).[38] In Texas, the hardest hit state, the cumulative cost of damages was over $13,000 per person (NOAA, 2024). The frequency of these events has risen steadily by decade, from an average of three events per year in the 1980s, to 13 in the 2010s, and 21 between 2019 and 2024 (Chart 31) (NOAA, 2024, 2025). Alongside this increasing frequency, the inflation-adjusted average cost per year rose by a factor of more than six from $21B in the 1980s to $131B from 2019-2024 (NOAA, 2024, 2025).

Chart 31: US Billion-dollar disasters due to weather and climate-related events, 1980-2024 (2024 $US)



Source: NOAA (2025)

Between 2015 and 2024, 190 billion-dollar disasters directly caused at least 6,300 fatalities and approximately $1.4 trillion in damage in the US (NOAA, 2025). Damage costs were $183 billion in 2024, while in the first half of 2025 they amounted to $101 billion, including $61 billion for the Los Angeles wildfires (Climate Central, 2025).

In the worst years, these costs – which do not include damage from less severe disasters, or output or secondary losses – have amounted to a significant proportion of US GDP. In 2005, when Hurricane Katrina hit New Orleans, damage costs from all major US weather and climate disasters exceeded 1% of national GDP. In 2017, when Hurricane Harvey flooded Houston, Hurricane Irma hit Florida, and Hurricane Maria devastated Puerto Rico, total damage from all such disasters approached 2% of US GDP (NOAA, 2024).

Direct property damage costs associated with extreme weather are often very high relative to national or regional GDP. First responder costs, and lost output due to business closures,

[38] This analysis excludes events with less than $1 billion in damages in 2024 dollars, but includes 57 events since 1980 that were originally below the billion-dollar threshold but later exceeded $1 billion in 2024 dollars.

evacuations and second-order losses are also often very significant relative to regional and national capacity. For instance:

- In 2017, when Hurricanes Irma and Maria hit Puerto Rico, damage costs estimated at $92 billion exceeded Puerto Rican GDP of $79 billion (Anagnostakos, 2023).
- The 2022 Pakistan floods due to torrential rains and unprecedented glacier melt caused damages of $US 15 billion, equivalent to 5% of GDP, and were estimated to have reduced GDP by 2.2% (Government of Pakistan *et al.*, 2022). (Text Box 1.)
- Severe flooding in Thailand in 2011 affected over 13 million people, inundated 6 million hectares of land and caused widespread damage to manufacturing industries. Damage costs were assessed at $US 46.5 billion or 13% of GDP; growth declined by 1.1 percentage points from pre-flood projections (World Bank, 2012).
- Dominica was struck by Tropical Storm Erika in 2015, cutting off water and electricity supplies and causing damage estimated at $US483 million, equivalent to 90% of GDP (World Bank, 2015). Two years later, Hurricane Maria wiped out 90% of crops, livestock and homes, resulting in losses and damages equivalent to 226% of GDP (IMF, 2021).
- In 2021, British Columbia experienced three separate weather disasters. A June heat dome led to 619 heat-related deaths and killed 650,000 chickens. Subsequent summer wildfires destroyed the town of Lytton and the community of Monte Lake and caused 33,000 people to be evacuated, while widespread smoke caused poor air quality throughout the province and beyond. Extreme rainfall and flooding in November caused severe damage to highways, bridges and rail lines, and flooded farms in the Abbotsford area, killing a further 630,000 chickens and 12,000 pigs. These events resulted in insured damages of $870 million and uninsured damages estimated at between $1.7 billion and $5.4 billion, or between 1% and 2% of provincial GDP. In addition, income losses and incremental public expenditures (largely for firefighting and replacement of infrastructure) totalled between $8 billion and $10.8 billion, amounting to approximately 3% of provincial GDP (Lee & Parfitt, 2022).
- In 2025, Hurricane Melissa killed at least 75 people and caused estimated damages across the Caribbean of $US50 billion. In Jamaica, damage was assessed at a minimum of $6-7 billion, equivalent to 30% of GDP, and GDP declines in the range of 8%-13% were anticipated.

In addition to damaging physical capital and reducing GDP, extreme weather damages human capital via its impacts on injury, illness, mental health and premature 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).

Text Box 1: The 2022 Pakistan floods:
A case study of how extreme weather affects productivity

The 2022 Pakistan floods provide an instructive example of how an extreme weather disaster affects productivity in both the short and longer term. In 2022, Pakistan was hit by unprecedented flooding that put one third of the country underwater. Attribution analysis found that the rainfall that caused the flooding was 75% more intense because of climate change.* The flooding displaced 8 million people, killing 1,700, and damaged or destroyed millions of homes as well as businesses and key infrastructure. Agriculture was severely affected, with 1 million livestock killed and 4.4 million hectares of agricultural land inundated or damaged, resulting in crop losses of 60-80% for cotton, rice and sugarcane.

A multi-institutional international assessment found that flood damages, i.e. the direct costs of destroyed or damaged physical assets, totalled $15 billion US, equivalent to 4.8% of 2022 GDP. In addition to these direct costs was a further $15 billion in economic losses, including declines in output in productive sectors, lower revenues and costs for additional services such as rubble removal, temporary shelters, and ad hoc vaccination campaigns. The decline in 2022 GDP resulting directly from the floods was estimated at 2.2%. Agricultural damages had spillover effects into other sectors; for instance, losses of cotton crops resulted in large output losses in the textile industry.

Beyond the immediate productivity impacts were longer-term negative impacts resulting from prolonged decreases in productive capacity due to: time lags in the rebuilding of productive capital and rehabilitation of damaged or contaminated agricultural land; diversion of funds away from new productive capital investments to replace and repair damaged capital; and damage to human capital.

Government recovery plans included reconstruction timeframes of up to five years to repair or replace damaged or destroyed assets that included:

- 40% of railways (3,100 km) and 3% of roads (8,300 km);
- 17,205 educational institutions with 2.6 million enrolled students;
- 13% of all health facilities.

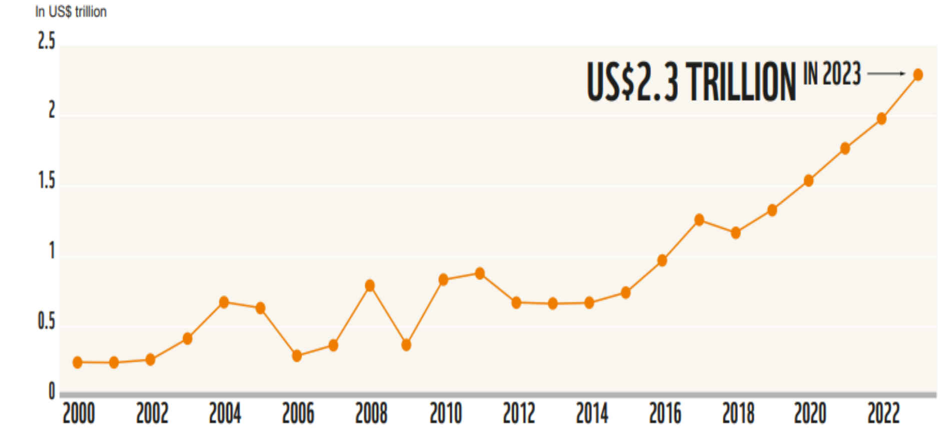
The assessment also found that the floods would trigger substantial losses to human capital via impacts on health and education. Food shortages, lack of safe drinking water and sanitation, disease outbreaks, vaccination delays and reduced access to health care, each affecting between 1.2 and 7.6 million households, would worsen overall health and raise the incidence of growth stunting among children; while prolonged school closures and lack of education access would reduce learning, with long-lasting impacts on productivity.

The multi-institution study concluded that the overall damage to the economy's productive capacity would reduce growth prospects over an extended period.

**Quantitative impacts cited are from: Government of Pakistan et al. (2022)*

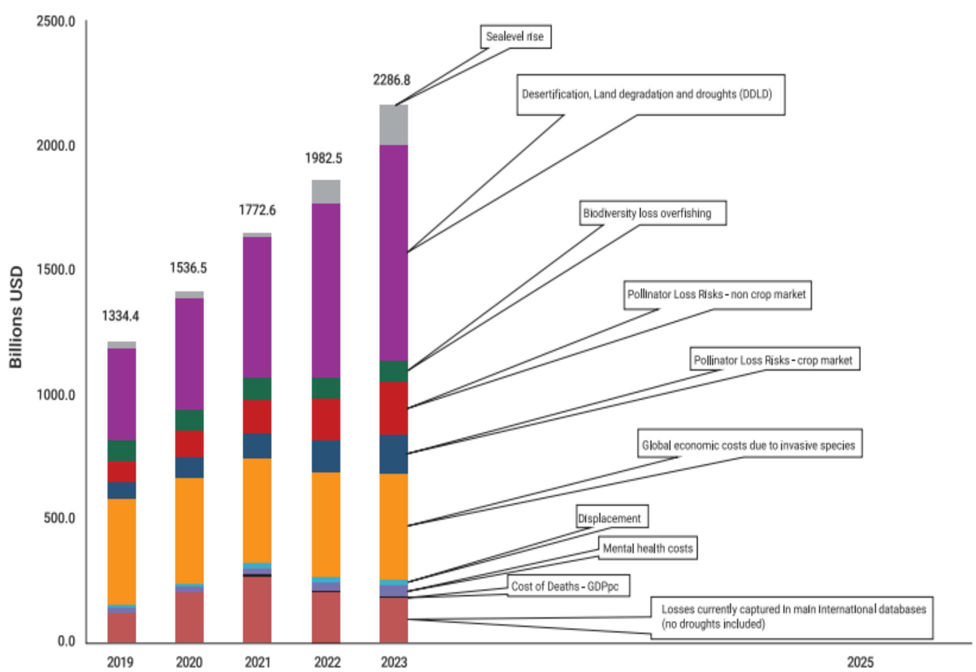
The United Nations Office for Disaster Risk Reduction (UNDRR) has estimated the total cost of global disaster damage, including indirect and ecosystem costs, at $2.3 trillion in 2023, or 2% of global GDP (Charts 32 and 33) (UNDRR, 2025).[39]

Chart 32: Global disaster damage, including indirect and ecosystem costs $US trillion



Source: UNDRR (2025)

Chart 33: Reported global cost of disasters with additional indirect impacts ($US billions)



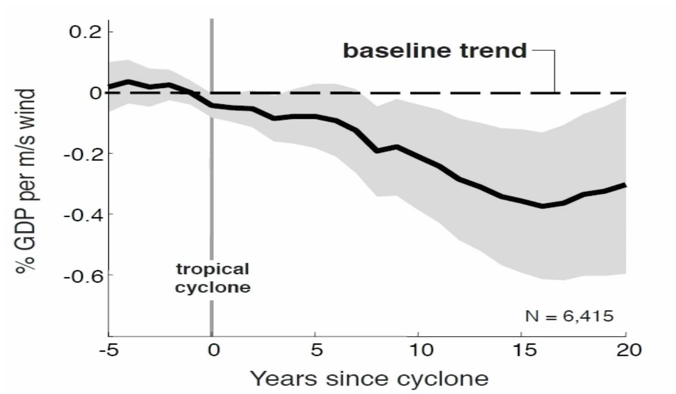
Source: UNDRR (2025)

[39] These costs include: deaths; displacement; mental health impacts; invasive species; desertification; land degradation and droughts; sea level rise; biodiversity loss; pollinator loss (crop and non-crop costs).

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, 2021).[40] Between 1960 and 2018, it found that climate disasters reduced labour productivity in affected countries in the year following the disaster by an average of 0.5%. The effects were persistent; after three years, severe climate disasters lowered national labour productivity by about 7% in affected countries, primarily through weakened MFP. Because the frequency of climate disasters rose sharply over that period (tripling between 1960-79 and 2000-18), 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 (Dieppe, 2021).

Hsiang and Jina (2014) assessed the macroeconomic impact of cyclones and hurricanes, classified by wind speed, using global data on 6,700 cyclones between 1970 and 2008. They concluded that cyclones strongly reduce GDP growth; that the negative impact persists for 15 years before partial recovery begins; and that full recovery to baseline does not occur even by the 20-year point (Chart 34).

Chart 34: Macroeconomic impact of a cyclone or hurricane
(% change in GDP per unit of wind speed)



** m/s = metres per second. 1 m/s = 3.6 km/hr.*
Source: Hsiang & Jina (2014) Hsiang (2025)

The IMF (2017) also assessed the macroeconomic impact of cyclones between 1950 and 2016. It too found very persistent economic impacts, with real GDP per capita 1% lower on average after seven years in economies hit by cyclones (2% for islands and 2.5% for small states); and no full recovery even after twenty years.

Following extreme weather events rebuilding may be time-consuming, particularly where widespread losses are incurred and construction capacity is limited, meaning that output losses

[40] 6,410 adverse events worldwide were analyzed, including climate disasters, biological disasters, geophysical disasters, wars and financial crises.

can persist over several years. Repeated cycles of major damage and rebuilding put pressure on scarce construction capacity and resources, raising costs for other purposes

Where losses are uninsured, reconstruction and recovery can be expected to be even slower, or not to occur at all, as many economic actors will be obliged to secure refinancing to rebuild demonstrably risky assets. Swiss Re finds that only 38% of global economic losses from extreme weather and natural catastrophes are covered by insurance, with 10-year national average figures ranging from lows of 6% in China and 9% in India to 79% in the United Kingdom (Swiss Re, 2024a). Government funds may provide a partial, but very rarely complete, backstop for uninsured losses.

Rising incidences of flooding and extreme weather often result in rising insurance rates, and can also produce insurance deserts in high-risk regions where insurance companies decline to extend standard forms of new coverage – a phenomenon already occurring in a number of places, including parts of Florida and California, where many property owners have been pushed into high-risk market segments and to insurers of last resort, which are often government-backed (Smith *et al.*, 2024). The share of uninsured homes in the US grew from 5% in 2015 to 12% in 2023, with higher proportions in some states such as Florida, where it is 15-20% (III & Munich Re, 2023). US property prices have also been affected by the insurance shock, with home prices in the 10% of postal codes most vulnerable to catastrophes depressed by an average of $44,000 in 2024 (Keys & Mulder, 2025).

In the US, home insurers have recorded losses in seven of the past eight years (2017-2024) due to the accelerating pace of extreme weather, with total underwriting losses of $US 15.2 billion – the largest in a century – in 2023 (Graham *et al.*, 2024; Hemenway, 2025).

Globally, the cost of reinsuring properties against extreme weather has risen 2.4 times since 1992 (Smith *et al.*, 2024), and rising insurance premiums have been described as a de facto 'carbon price' on consumers.

Munich Re indicates that annual global weather-related insurance losses rose nearly seven-fold, in constant 2018 dollars, between the 1980s and the 2010s, from US$10 billion to US$68 billion (Munich Re, 2025a). And Swiss Re estimates that global insured losses from catastrophes more than doubled as a percentage of global GDP since the 1990s (Swiss Re, 2024a).[41]

Extreme weather also raises the cost of doing business in a range of other ways by making it necessary for individuals and enterprises to incur prevention and adaptation costs for measures such as flood prevention and protection, more resilient building construction, and increased need for air conditioning and air filtration equipment. It can raise health care costs without net improvement in health outcomes. As well, school closures, housing disruptions and mental health effects among children can negatively affect human capital formation.

[41] Swiss Re estimates that global insurance payouts from catastrophes are currently growing at 5-7% annually, and that the insurance loss burden relative to GDP could double over the coming decade (Swiss Re, 2024b).

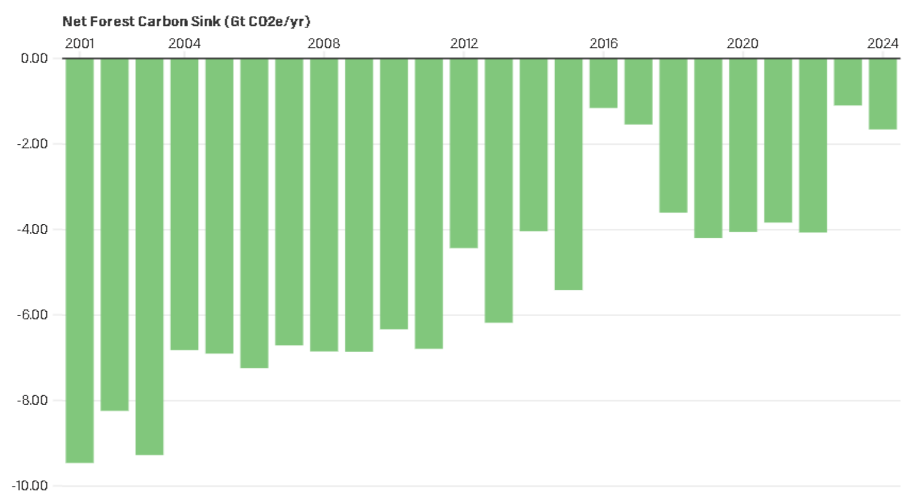
Wildfires

Climate change has significantly raised the incidence and extent of highly destructive wildfires in recent decades (UNEP, 2022b). Globally, the frequency of extreme wildfire events has more than doubled over the past two decades, driven largely by an 11-fold increase in extreme fire events in the coniferous forests of western Canada and US, a seven-fold increase in the boreal forests of North America and Russia, and a 20-28-fold increase in Amazonia (Cunningham *et al.*, 2024; Jones *et al.*, 2024). Wildfires are increasingly occurring in areas where they previously did not normally occur, such as the Arctic and the Amazon (UNEP, 2022b). The six most extreme wildfire years have all fallen within the past seven years. Their rising incidence and growing expanse have been linked to rising temperatures and aridity, and to related widespread drying of wildland fuel, heightening fuel flammability (Ellis *et al.*, 2022; Hausfather, 2018; IPCC, 2023).

Wildfires have become a growing source of forest loss. They now burn more than twice as much tree cover annually as two decades ago, and account for nearly half of annual forest loss – an average of 44% in 2023 and 2024 (MacCarthy *et al.*, 2025). The steepest increases in fire-related losses have been in northern boreal forests, which now account for over 60% of annual fire losses; fire losses have also accelerated in tropical forests (MacCarthy *et al.*, 2025).

GHG emissions from forest fires have grown so large that, in combination with other forest changes, they have acted to sharply reduce net GHG absorption by global forests. In 2023 and 2024, net CO2 absorption had declined to only 15% of absorption from 2001-2003 (Chart 35).

Chart 35: Declining global net forest carbon sink: Forest carbon dioxide absorption minus GHG emissions



Source: Harris & Rose (2025)
Forest greenhouse gas emissions include carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) while removals include carbon dioxide only.

There have been exceptional regional forest losses in recent years. 189,000 square kilometres were lost in the Australian wildfires of 2019-20 (Johnston *et al.*, 2021). In the Amazon, increased fire frequency and duration have reduced tree biomass and carbon stocks by 25%

(UNEP, 2022b). In 2023, 185,000 square kilometres were lost in Canada, approximately 5% of Canada's forested area, and GHG emissions from forest fires exceeded economy-wide emissions from all human sources (Byrne *et al.*, 2024). Indeed, in 2023 forest fires emitted an estimated 6,687 megatonnes of CO2 globally, more than double the EU CO2 emissions due to burning of fossil fuels (FAO, 2024a).

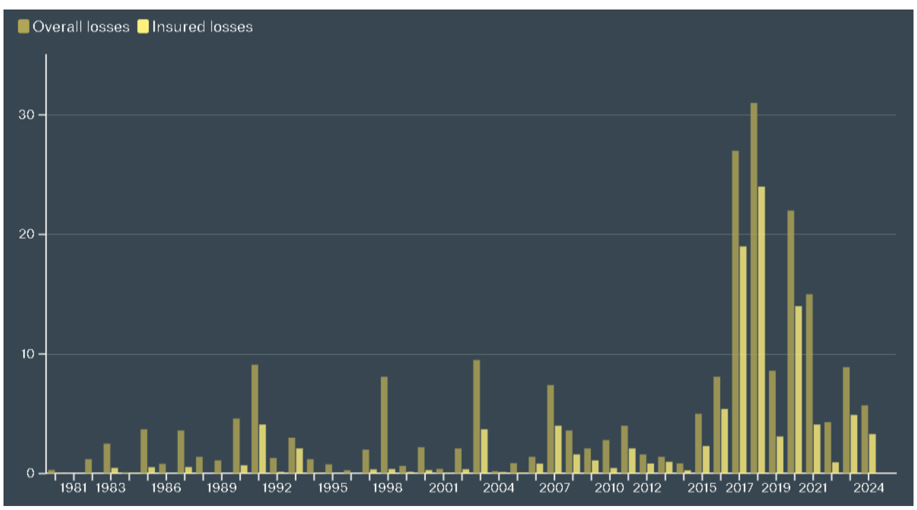
Wetlands have also been destroyed; in 2020, one third of the vegetation in the Brazilian Pantanal, the largest tropical wetland in the world, was destroyed by fire linked to extended severe drought, killing 17 million vertebrate animals, including 170,000 primates (UNEP, 2022b; WWF, 2021).

Among the other environmental consequences of increased forest fire activity are:

- Loss of water cycle regulation and water filtration services;
- Large drops in wildlife populations;
- Loss of soil organic carbon and breakdown in soil structure;
- Loss of water absorption and retention capacity;
- Greater runoff and erosion, including mudslides and landslides.

The real global cost of property damages from wildfires has escalated significantly over the past decade (Chart 36). For 2015 to 2024 that total was estimated by Munich Re at $US 136 billion ($2024), of which $80 billion was insured.

Chart 36: Wildfire property losses worldwide, 1980-2024
(US$ billion, inflation-adjusted)



Source: Munich Re (2025)

Wildfires have had significant impacts on national and regional economies and on human health.

- Economic losses due to fires in the **Brazilian Amazon** were assessed for the 1996-1999 period, which included a severe drought (Da Motta *et al.*, 2002). The authors estimated that the destruction of pasture, fences, forests, and impacts on human health of increased particulate matter resulted in annual average costs of over US$100 million, or nearly 9% of the region's GDP (UNEP, 2022b).

- The **Australian** fires of 2019-2020 were driven by unprecedented forest dryness resulting from an extended rainfall deficit and high temperatures (Ellis *et al.*, 2022). The fires directly killed 33 people and an estimated 3 billion animals (Johnston *et al.*, 2021). In addition, they caused 4,753 hospital admissions and 429 smoke-related premature deaths, and yielded smoke-related health costs of AU $1.95 billion (Johnston *et al.*, 2021). Food production losses included over 100,000 livestock deaths and were estimated at AU $2 billion, or 3% of national agricultural output over that period (Bishop *et al.*, 2021). In addition, insured losses for damage to property, which did not cover all losses, totalled AU $2.3 billion (Bishop *et al.*, 2021). In total, these economic losses – which do not include the environmental cost of carbon emissions – were equivalent to 0.5% of Australian GDP in 2020.
- **Indonesia** has experienced increasing fire incidence since the 1980s due to forest degradation, peatland drainage and expansion of crops such as palm oil. Forest fires in 1997-98 were estimated to have cost in the range of US$1.6–2.7 billion from damage to timber and crops, and from smoke-related impacts on tourism and transport. Smoke pollution was estimated to have caused 15,600 excess deaths, at a cost of US$ 15 billion (Almeida *et al.*, 2024). In 2015, economic losses from the severe fires escalated to US$16.1 billion, equivalent to 1.9% of GDP (Glauber *et al.*, 2016). Immediate health costs totalled US$151 million, and 5 million children missed school due to closures. Subsequently, in 2019, fires caused economic losses of US$5.2 billion or 0.5% of GDP (World Bank, 2019).
- In the **US**, a 10-year review found that the direct costs of wildfires ranged between $8 billion and $63 billion ($2016) per year, including firefighting costs and disaster assistance. The additional annual cost of economic losses was estimated at $63-285 billion ($2016), including direct deaths and deaths from wildfire smoke (3,000-21,000 per year at $5 million per death), timber losses of $6-10 billion, evacuation costs, and loss of value of structures. The annual total of these costs and losses ranged between $71billion and $348 billion ($2016 US) (Thomas *et al.*, 2017).
- One study calculated the average annual economic costs of wildfires in **California** between 2017 and 2021 at over $117 billion (Kosmala-Dahlbeck *et al.*, 2025).
    - The 2018 Camp Fire destroyed over 18,000 structures and resulted in total damages of $19 billion, or 0.68% of California GDP (Kosmala-Dahlbeck *et al.*, 2025). The 2018 California wildfires were estimated to have caused US$4.5 billion in damages to household property, in addition to 104 direct fatalities and 3,652 deaths due to air pollution. Associated healthcare costs were estimated at US$32.2 billion (1.1% of California GDP) due to increased mortality, medical expenses and work time lost (Almeida *et al.*, 2024).
- The catastrophic fires in the Los Angeles area in January 2025 claimed at least 29 lives and destroyed over 16,000 structures. Total property and infrastructure losses of $76-131 billion were caused, including insured losses of up to $45 billion. The fires were estimated to cause a 0.5% decline in county-level GDP, amounting to $4.6 billion, and a wage loss of $297 million for local businesses and employees (Li & Yu, 2025).

The incidence and expanse of highly destructive wildfires have risen in North America over several decades. In the summer of 2023, 232,000 Canadians were evacuated due to widespread wildfires, many individuals for weeks, disrupting all normal activities and completely closing down local economies. Evacuees comprised two thirds of the population of the Northwest Territories, including the 20,000 residents of the capital Yellowknife. Wildfires in Canada and the US over the past dozen years have resulted in large-scale or complete destruction of whole towns: Slave Lake (2011), Fort McMurray (2016), Paradise (2018), Lytton (2021), Lahaina (2023), Jasper (2024) and communities around Los Angeles (2025). In addition to trauma and loss of life, these incidents resulted in high fire response expenditures, enormous damage to homes and infrastructure, complete economic disruption, and long-term dislocation of many individuals from their homes and livelihoods. (Text Box 2).

Text Box 2: Economic impacts of the Fort McMurray Fire (2016)

The Fort McMurray fire provides an example of the degree of disruption caused by wildfires in settled areas. In May 2016, a rapidly growing forest wildfire reached the outskirts of Fort McMurray, in the heart of Alberta's Athabasca oil sands. 90,000 people were evacuated from the town, as were all workers in the nearby oil sands operations; most remained away from their homes for at least a month (Public Safety Canada, 2024). Two fatalities occurred, in an evacuation-related accident, and the fire destroyed 2,400 homes and businesses and burned 5,800 square kilometres of land (PSC, 2024). At the peak of the fire activity, over 2,000 firefighters were combatting the fires daily, including 500 from the US, Mexico and South Africa (PSC, 2024).

The direct cost of damage to property was assessed at $4.1B Cdn ($2016) (Alam et al., 2017). However, the total costs associated with the fire were much higher, $10.9B Cdn. This includes lost oil sands production ($1.7B); lost production in other sectors ($1.4B); firefighting and disaster recovery expenditures ($468M); foregone municipal and provincial revenue ($186M); lodging and living expenses ($353M); lost timber value ($2.1B); carbon release ($850M); and ecosystem damages ($183M) (Alam et al., 2017). Insurance payouts were estimated at $3.6B Cdn. (PSC. 2024). The total costs of $10.9B associated with the Fort McMurray fire represented 0.6% of Canadian GDP in 2016, and 3.7% of Alberta GDP (Statistics Canada, 2025a); these constitute deadweight economic losses to the Canadian and Alberta economies. Lost production alone ($3.1B) accounted for over 1% of Alberta GDP in a year in which Alberta GDP contracted by 3.8%; and for 0.2% of Canadian GDP in a year in which it grew by only 1.0% (Statistics Canada, 2025a).

Fire-related costs have extended well beyond those regions directly impacted by fire. The 2023 Canadian wildfires produced smoke that spread over much of eastern Canada and the United States, resulting in poor air quality and multiple public health advisories to avoid outdoor activity. In consequence, numerous outdoor sporting, cultural and recreational activities were cancelled, and many tourist, hospitality and restaurant businesses suffered economic losses.

Studies have linked wildfire smoke to significant increases in illness and death (UNEP, 2022b). Globally, exposure to wildfire smoke is estimated to have caused 154,000 deaths in 2024 (Romanello *et al.*, 2025).

Wildfire smoke has been identified as the primary cause of spikes in air pollution levels in Canada and the United States in recent years, reaching the highest levels in 2024 since 2011 in the US and since 1998 in Canada (Greenstone *et al.*, 2025). In Canada, more than 50% of Canadians breathed air that exceeded the national standard of 8.8 μg/m³ in 2024, up from an average of less than 5% over the previous five years (Greenstone *et al.*, 2025). In the US state of California, an estimated 53-56,000 premature deaths between 2008 and 2018 were attributable to wildfire smoke, equating to an economic impact of $US 432-456 billion (Connolly *et al.*, 2024).

In the Brazilian Amazon, smoke from deforestation fires has been found to be responsible for almost 3,000 premature deaths annually (UNEP, 2022b).

In addition, increasing wildfire incidence has significantly raised firefighting costs. In the US, annual firefighting expenditures by federal agencies rose by 170% between 2010 and 2020, to $US 1.9 billion (UNEP, 2022b). In Canada, annual expenditures for national wildfire management have risen by approximately $Cdn 120 million per decade since the 1970s, to a current level of near $Cdn 1 billion; this represents a real increase of approximately 60% (UNEP, 2022b).

A recent study examined the US labour market impact of air pollution from wildfires (Borgschulte *et al.*, 2022a, b). Between 2007 and 2019, regions of the US were covered by wildfire smoke for an average of 20 days per year, with nearly every state experiencing some smoke exposure (Borgschulte *et al.*, 2022a, b). The authors found that each day of smoke reduced quarterly per capita earnings in affected regions by .10%; it concluded that total US labor income was reduced by an average of 2% per year over this twelve-year period due to the effects of wildfire smoke (Borgschulte *et al.*, 2022a, b).

Labour productivity and human capital

Climate change has both immediate short-term effects on labour productivity and longer-term impacts via its effects on human health and human capital development.

It is well established that heat stress diminishes labour productivity. Labour productivity declines by 25% at exposure to temperatures above 25° C; by 50% above 33-34° C, and by 80% above 35° C (Heal and Park, 2016; Kjellstrom *et al.*, 2019).

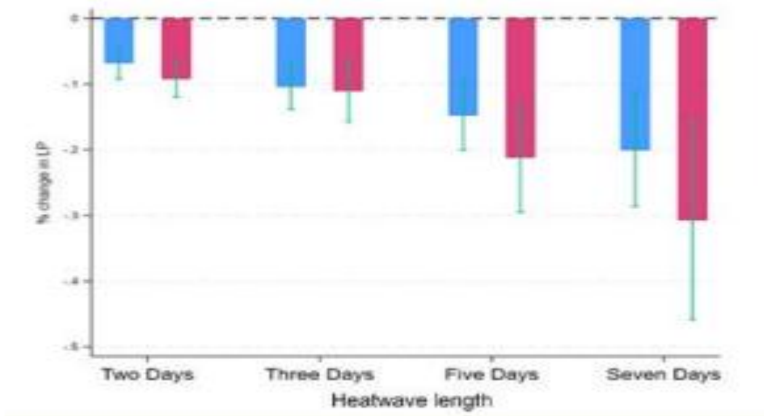
Workers in outdoor occupations such as agriculture and construction are particularly affected. In 1995 approximately 1.4% of total working hours were lost worldwide due to heat; that proportion has since risen, and is expected to reach 2.2% by 2030 (Kjellstrom *et al.*, 2019). In 2023, heat exposure led to the loss of 512 billion global work 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% over the past four decades (Parsons *et al.*, 2022). These losses comprised 2.6% of global GDP in 2017, and more than 10%

of GDP in some countries. Globally, the increment in annual productivity losses attributed to rising temperatures was equal to 0.3% of global GDP in 2017.

OECD studies have found that a single additional heatwave can have a demonstrable negative impact on labour productivity (Chart 37).

Chart 37: Percentage change in labour productivity due to an additional heatwave, 2000-2021, 23 OECD countries



Source: Costa et al. (2024)

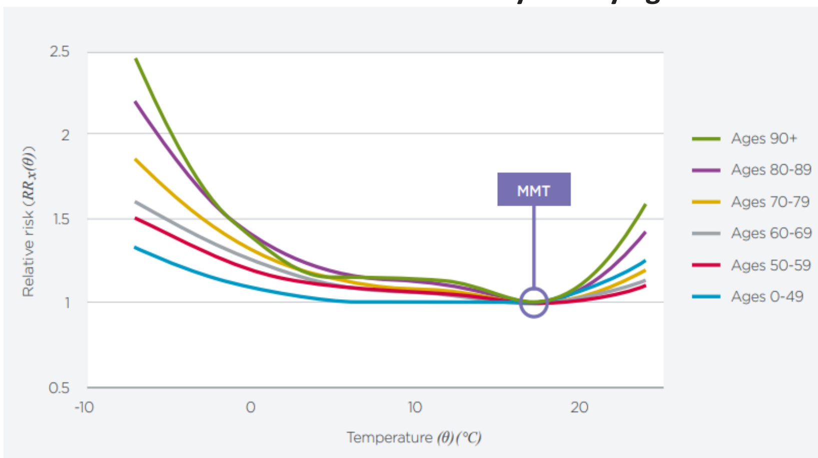
Outdoor work can be cancelled during extreme heat events where mandated by labour standards, directly affecting output in industries such as construction, agriculture, tourism and recreation. Often working hours are simply reduced in response to high temperatures. More frequent hot days can also raise costs for industries where work is primarily indoor by raising the need for air conditioning. Similarly, poor air quality related to wildfire smoke can also heighten the need for more effective indoor air filtration.

Over the longer term, the health impacts of extreme weather are well established, with higher temperatures, particularly heat extremes, resulting in higher rates of illness, hospitalization and premature death (Portner *et al.*, 2022), with clear implications for labour supply and productivity. Climate change has also been linked to greater spread of disease vectors, such as those that produce Lyme disease and dengue fever, and to mental health challenges, including stress and anxiety (Portner *et al.*, 2022).

Because many classrooms are not air-conditioned, excessive heat often results in school closures, leading to more frequent schooling interruptions. This directly affects the productivity of parents who need to make alternate child care arrangements or rearrange work schedules, and also affects the human capital development of students.

Extreme heat also affects human capital directly via its impacts on human health and mortality, reducing life expectancy and productive time. Extremely hot and cold days result in excess mortality, producing a U-shaped mortality curve. In England and Wales, the daily average temperature corresponding to minimum mortality rates is 17°C (Chart 38). In other parts of Europe, the MMT is 18°C (Gallo *et al.*, 2024).

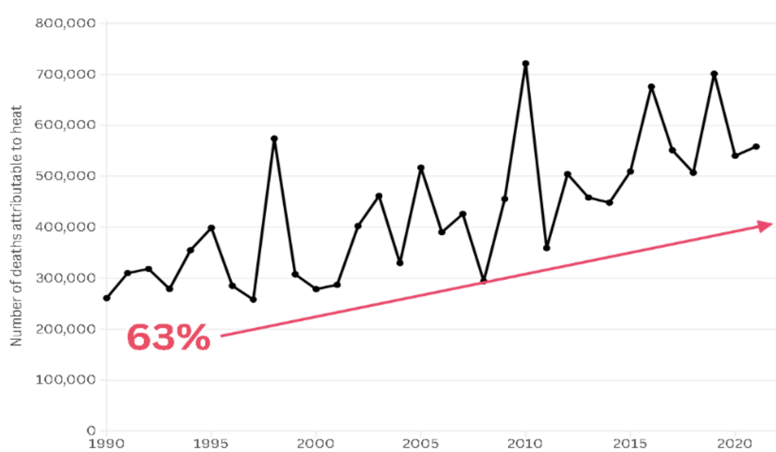
Chart 38: Relative mortality risk by age



Source: Kuona & Gong (2025)
MMT: The minimum mortality temperature (MMT) is the daily average temperature corresponding to the lowest levels of mortality. Data is from England and Wales.

Globally, as the climate has warmed, heat-related mortality has increased steeply by decade, resulting in a 63% increase in heat-related deaths since the 1990s (Chart 39). Between 2012 and 2021, an annual average of 546,000 deaths was attributable to heat (Romanello *et al.*, 2025). [42]

Chart 39: Global number of deaths attributable to heat, 1990 to 2021



Source: Romanello et al. (2025)

Sectoral impacts: Agriculture

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

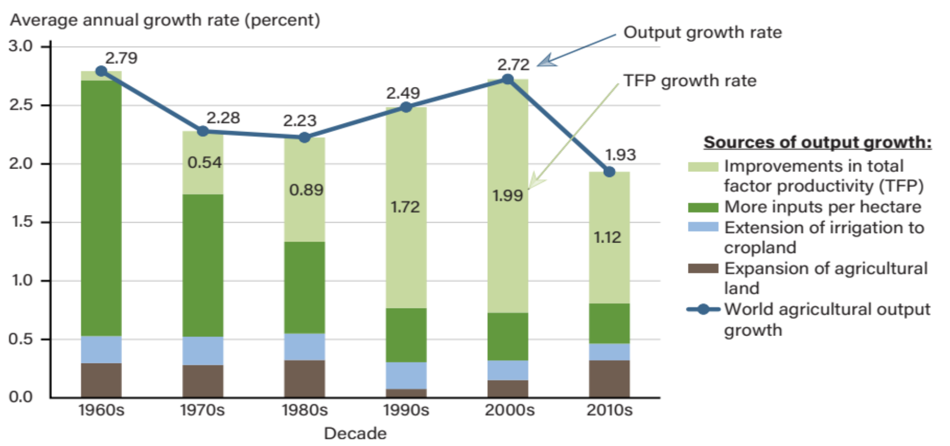
[42] There are currently more deaths due to cold than to heat globally, by a ratio of approximately 9 to 1 (Alahmad *et al.,* 2025). However, a European study found that, due to the steepness of the mortality curve to the right of the MMT, the increase in heat-related deaths due to rising temperatures consistently exceeds any decrease in cold-related deaths (Masselot *et al.*, 2024).

accounts for only about 4% of global GDP, it can have disproportionately large dynamic effects, as food scarcity is a well-established driver of migration and economic dislocation (IOM, 2024).

Global agricultural productivity and TFP grew strongly from 1960 through 2010 (Chart 40). This permitted global agricultural production to grow more quickly than world population over the latter part of the 20th century (FAO, 2015b; Fuglie *et al.*, 2024). From 1961 to 2000, global food production grew by 146%, well exceeding global population growth of 98%; accordingly, food supply per capita rose by 24% and real food prices trended downward throughout this period (FAO, 2015b). From the 1960s through the 1980s, production growth was largely driven by rapid intensification of inputs such as fertilizers and irrigation (FAO, 2015b); after the 1980s, total factor productivity (TFP) became the key driver of output growth (Fuglie *et al.*, 2024).

Global agricultural productivity and TFP growth slowed significantly after 2010, to an average of only 1.1% per year between 2011 and 2020 – barely exceeding global population growth, which averaged 1.0% over the same period. This decline was attributed to climate-related drought, heatwaves and floods (Fuglie *et al.*, 2024).

Chart 40: Sources of growth in world agricultural output by decade, 1961-2020



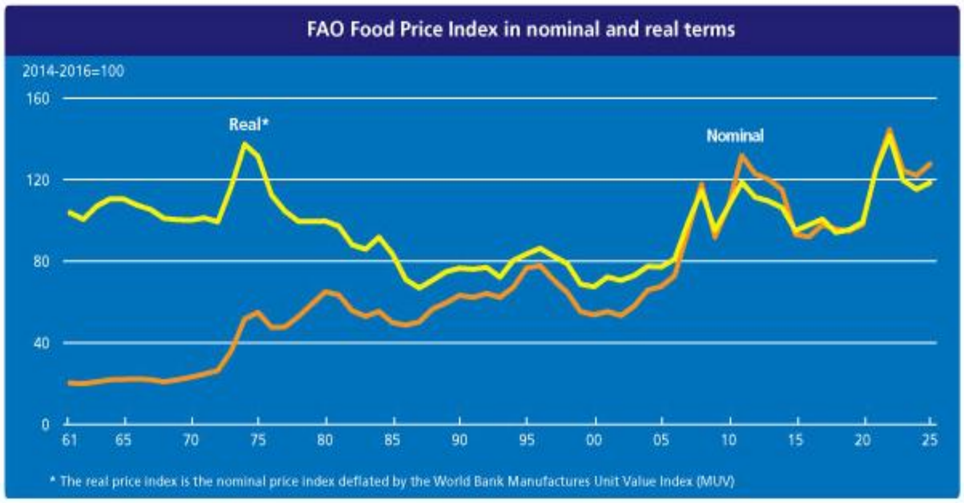
Source: Fuglie et al., 2024

The slowdown in agricultural TFP growth vis-à-vis global population growth occurred in tandem with a reversal of the previous longstanding trend of declining real food prices. The US Agricultural price index, which had previously exhibited a declining trend in real prices for over 80 years, has more than doubled since 2000 (Fuglie *et al.*, 2024). Similarly, the FAO global real food price index, which had been on a declining trend since 1960, except for a bounce coinciding with the 1973-74 oil price shock, nearly doubled between 2000 and 2025 (Chart 41) (FAO, 2025).[43] Food prices are now rising more quickly than other prices in a majority of

[43] The FAO food price index is a measure of changes in the average international prices of a basket of five commodity groups: meat, dairy, cereals, vegetable oils and sugar. The real food price index is the nominal price index deflated by the World Bank Manufacturers Unit Value Index (FAO, 2025).

countries (World Bank, 2025b). Over the same period, the global number of food-insecure people also rose (Fuglie *et al.*, 2024).

Chart 41: FAO Food Price Index, Nominal and Real*



* *Real price index = nominal price index deflated by World Bank Manufactures Unit Value Index.*
Source: FAO (2025)

Climate change associated with a 1°C increase in global temperature was found by a separate study 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).

Numerous studies have also examined the impact of climate change on crop yield for a range of crops in varying locations, with findings that climate change typically adversely affects yields.[44] The IPCC has concluded that climate change has slowed agricultural productivity growth via its negative impacts on crop yields (IPCC, 2023). The impacts of temperature on crop yield are highly significant. The FAO has estimated that for every 1°C increase in global temperatures, average global cereal yields decline by 3%-10%, implying cumulative global yield declines of 4.5%-15% to date due to a 1.5°C increase (FAO, 2024b, d).

Ray *et al.* found overall negative impacts of climate change between 1974 and 2008 on a range of major global crop yields, including staples such as rice, wheat and cassava (Ray *et al.*, 2019). Crops particularly affected by climate change were barley (8% global yield decline) and palm oil (13% decline). European agricultural production was strongly affected, with yields for all dominant crops in western and southern Europe down by between 6% and 21% due to climate

[44] Crop yield studies provide a less comprehensive indicator of changes in multifactor productivity than those that assess overall changes in MFP, as they do not encompass the entire set of crop and livestock commodities and do not take account of factors such as the effect of heat stress on farm workers or adaptive adjustments by farmers. However, changes in yield when inputs are held constant can be considered a direct measure of MFP (Beckman, 2024).

change. In eastern and northern Europe, barley and sorghum yields declined by 9% due to climate change, while maize yields fell by 24%.

Two other recent studies found consistently negative temperature impacts on crop yields at the global scale for four major crops – wheat, rice, corn and soybeans – that together provide two thirds of human caloric intake. Both studies reached essentially the same conclusions: that each degree Celsius increase in global mean temperature reduces global yields of wheat by 6%, rice by 3%, corn by 7%, and soybeans by 3% (Zhao *et al.*, 2017; Bigolin & Talamini, 2024). Mean annual temperatures in areas where these crops are grown have increased by approximately 1°C over the past century (Zhao *et al.*, 2017). Bigolin and Talamini evaluate the annual global economic losses from climate-related lower yields of these four crops at $US 43 billion.

In the US, research has shown detrimental impacts to corn, soybean and cotton crops – which account for half the value of US crops – on days exceeding 30°C, which have increased in frequency with climate change (Council of Economic Advisers, 2022). In California, extended drought resulted in the Central Valley Project, which supplies water to cities and farmers, completely cutting water to farmers in four out of ten years prior to 2023, with ensuing production declines (CEA, 2023).

Agriculture is particularly vulnerable to extreme weather events, and it is well established that such events have negatively affected agricultural productivity via negative impacts on crop yield, including losses of entire crops. The FAO found that disaster events reduced global agricultural GDP by growing amounts between 1972 and 2022, averaging 5% over the entire period; this constituted an annual drag of 0.2% of global GDP (FAO, 2023). Overall agricultural losses from disasters have increased since the 1990s and have affected a widening range of countries and products.

Underlying the FAO's finding are many supporting studies. One global study examined the impact of 2,800 extreme weather events between 1964 and 2007 on cereal production (Lesk *et al.*, 2016). It found that, in affected countries, droughts and extreme heat each reduced national cereal yields in the same year by an average of 10%, causing a cumulative global loss of over 3 billion tons of cereal production over the entire period. Production losses rose significantly over time, possibly due to increases in drought severity and duration. Droughts caused national production losses averaging 7% between 1964 and 1984, and 14% between 1985 and 2007. Over the final period examined, 2000-2007, 6% of global cereal production was lost due to extreme weather events (Lesk *et al.*, 2016).

In southern Australia, climate change has been linked to higher average temperatures, steep reductions in growing season rainfall, and increased duration and intensity of droughts (IPCC, 2023). Sheng and Xu evaluated the impact of Australia's Millennium drought between 2002 and 2010 on Australian agriculture. They concluded that this extended drought acted to reduce agricultural total factor productivity by a cumulative total of 18% over that period, contributing significantly to the long-term slowdown in national agricultural TFP growth (Sheng and Xu, 2019). They observe that the long-term productivity impacts of climate change may greatly exceed the effects of short-term output losses, especially in cases of extreme climate conditions, via effects on farming practices, investments and expectations. Farmers discouraged by repeated low yields or by pessimistic views of their future prospects may simply stop farming. In addition, droughts are associated with soil degradation and loss due to wind erosion that can compromise future yields.

Labour productivity is the other important vector for climate impacts on agricultural productivity, due to the significant effects of heat on work output. Increasing heat has also raised the percentage of global agricultural working hours lost to heat stress, from 4.6% in 1995 to 8% by 2019 (Kjellstrom *et al.*, 2019).

In recent years, there have been numerous crop failures around the world for which climate change – evident as drought, storms or extreme temperatures – has been the primary cause. Examples include: Brazilian oranges, Spanish olive oil, California vegetables, Vietnamese coffee, Asian rice; West African cocoa; and British Columbia peaches (Dwyer, 2024; Edmond, 2024; FAO, 2024c; IMF, 2024; Kotz *et al.*, 2025; Savage, 2024a, b; Strachan, 2024; Wallace-Wells, 2024). These crop failures have generated upward pressure on food prices, causing huge price spikes for some food products. In southern Europe, a European Central Bank study concluded that the 2022 summer heat wave had raised food inflation by nearly a full percentage point in southern Europe (Kotz *et al.*, 2023).

Repeated crop failures have also compromised farm viability in many locations. For example, British Columbia farmers have experienced net losses every year since 2017, and collectively lost $457 million in 2024; farms in Nova Scotia and Newfoundland have also experienced net losses for several years (Statistics Canada, 2025b).

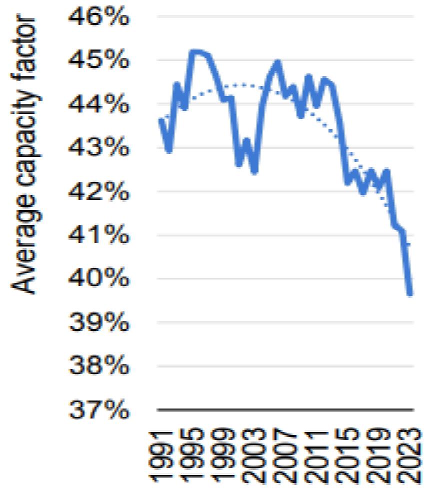
Other sectoral impacts

Rising water scarcity is a significant driver of rising costs in the mining sector associated with climate change, as are higher temperatures. Lepore and Fernando found that an increase in mean temperature of 1 C reduces mining productivity by nearly 3%; and that extremely wet conditions reduce mining productivity by nearly 1.5% (Lepore and Fernando, 2023).

Climate change affects electricity generation and transmission via multiple channels. Increasing aridity and more frequent and intense droughts lower water levels in lakes, rivers and reservoirs, jeopardizing hydro production and reducing available water for cooling of nuclear and thermal electric plants and spent nuclear fuel.

Hydroelectric power accounted for 14% of global electricity generation in 2024 and provides the majority of electric power in 28 countries (Wiatros-Motyka, 2024). It is the world's largest source of low-emissions power (IEA, 2025). 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 all, annual global hydropower output relative to installed capacity has been trending down since 2003, declining by over 10%, indicating reduced productivity in this sector (Chart 42).

Chart 42: Average annual global hydropower capacity factor, 1991-2023*



** The hydrocapacity factor is the ratio of hydropower output to installed capacity.*
Source: IEA (2024)

In recent years, numerous hydro generating facilities worldwide have been forced to cut power levels significantly or shut down altogether due to low water levels:

- In the US, drought caused national hydropower production to drop by 14% in 2021 (Bernstein *et al.*, 2021; Leslie, 2021). Colorado water levels have been dropping for years in the Lake Meade and Lake Powell reservoirs, jeopardizing hydroelectric production (Council of Economic Advisers, 2023).
- In South America, where hydropower accounts for nearly half (45%) of electricity generation, the worst drought in a century led to huge declines in power generation over the past few years, causing electricity shortages, rolling blackouts and price increases in heavily hydro-dependent countries including Brazil, Venezuela, Chile, Paraguay and Ecuador.
- Recurring droughts in South Africa since 2013 caused the Kariba Dam reservoir (the world's largest manmade reservoir) to drop to only 11% of capacity by 2019, disrupting electricity generation (Leslie, 2021).
- In China, a 2020 drought curtailed hydro production in Yunnan province by 30%, forcing the closure of a number of industrial facilities (Bernstein, 2021).

Extreme rainfall has also affected power generation in some cases. Flooding ensuing from megastorms in Malawi caused two power stations to go offline in 2020, reducing hydropower capacity by 80% (Bernstein, 2021).

There have also been numerous instances of severe damage to transmission and distribution lines due to weather events, with ensuing extended power outages affecting production in multiple industries:

- The 1998 ice storm in eastern Canada collapsed transmission towers, power lines and hydro poles, disrupting power supplies for days to a peak of 1.6 million people, temporarily displacing 600,000, preventing 2.6 million from working, and producing financial costs estimated at $5.4 billion (Statistics Canada, undated). The City of Montreal went dark as authorities chose to allocate scarce power supplies to maintaining water filtration plants, and virtually all businesses, schools, stores and banks were closed. It took a month before power was completely restored.
- Hurricanes Maria and Irma knocked out 80% of the Puerto Rican electrical grid in 2017, cutting power supplies to 1.5 million people for almost eleven months and requiring the rebuilding of most of the electrical transmission system (Jacobson, 2023).
- The February 2021 Texas deep freeze disrupted power for days to 4.5 million people. The power outage forced three major semiconductor plants to close, exacerbating a global semiconductor shortage, and also forced railway closures, severing transportation links between Texas and the Pacific Northwest for three days. (Leslie, 2022).

Significant impacts on transportation due to extreme weather and flooding have been well documented. These include bridge and highway closures, and cancellations of flights, ferries, trains, buses and subway service. These disruptions have immediate productivity effects in the transportation industry, but also knock-on impacts in many other industries via supply disruptions and delays, cost increases, business and institutional closures and cancelled events.

The increasing incidence of high temperatures and extreme heat has caused damage to transportation infrastructure such as buckling of pavement and warping of rails, raising repair and maintenance costs and leading to more rapid depreciation.

Bridge damage and collapse have become greater risks due to higher incidences of extreme rainfall and flash flooding, resulting in erosion from fast flowing water that undermines bridge foundations. Major bridge collapses following heavy rainfall have included the Kaneuchi Bridge in Yamamoto, Japan; a railway bridge in Chingquing, China; and a pedestrian bridge over the Mampituba River in Brazil (Barnard, 2023). In Colorado, a 2013 flood damaged 50 bridges and 500 miles of road, requiring over $700 million in infrastructure repairs, in addition to rebuilding costs for the 18,000 homes damaged (Davenport, 2024).[45] In Vermont, 100 bridges were damaged by heavy rainfall and heat in 2022 and 2023, and rebuilding them to more climate-resilient standards raised construction costs by 30-40% (Davenport, 2024).

Low water levels associated with increasing aridity have also limited water transportation in many places, including the Mississippi River and the Panama Canal (Mahoney, 2024; Rajanasakul, 2024). In 2024, access to the Panama Canal was limited by low water levels due to drought, reducing transit through the canal by one third and negatively impacting global value chains (Rojanasakul, 2024).

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[45] Paul Chinowsky, a professor of civil engineering at the University of Colorado Boulder, stated: “We have a bridge crisis that is specifically tied to extreme weather events. … These are not things that would happen under normal climate circumstances.” (Davenport, 2024)

In China, a study of half a million manufacturing firms found MFP declines correlated, ceteris paribus, with extremes of temperature, precipitation, humidity and wind speed (Zhang *et al.*, 2018). In India, labour productivity in manufacturing firms declined by 4-9% 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% due to the effects of climate change since 2015 (Sawyer *et al.*, 2022). In manufacturing, as in other industries, more extreme weather can also lead to faster depreciation of capital equipment.

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. These effects can magnify the economic impacts of climate change.

The risk of intergroup conflicts including wars has been found to be significantly heightened by climate change. A 1 standard deviation increase in temperatures was found to lead to an 11% increase in intergroup conflict (Burke *et al.*, 2015a). A separate large-scale study determined that armed conflicts produced the steepest productivity and TFP losses of all adverse events, with external wars reducing TFP by 10% after three years and labour productivity by 12% after three years (Dieppe, 2021).

Climate change and conflict are both recognized drivers 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.*, 2021; IMF, 2017; Kaczan and Orgill-Meyer, 2019). At the end of 2022, 61 million people globally were internally displaced due to conflict (28 million) and disasters (33 million); a further 35 million were international refugees, with the majority fleeing conflict or disaster (International Organization for Migration, 2024).

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, 2025). And since 1960, 8% of the rise in atmospheric CO_2 concentration has been found to be due to climate change weakening the land and ocean sinks, thereby contributing to further climate change.

b) Productivity impacts: Biodiversity and nature loss

Deterioration of Nature

Deterioration of nature encompasses biodiversity loss, pollution, and other resource depletion. It is increasingly recognized by serious economic actors that nature loss has become a major source of systemic risk to economies and financial systems, in parallel with climate change:

- The Network for Greening the Financial System (NGFS), a network of over 125 central banks and financial supervisors, concluded that nature-related risks, and failure to mitigate these risks, have significant macroeconomic implications, including for productivity (NGFS, 2024).
- The European Central Bank has acknowledged that biodiversity loss and degradation of nature make economies, companies and financial institutions increasingly vulnerable by undermining nature's ability to provide the ecosystem services on which economies are based (ECB, 2024).
- The World Bank is now mainstreaming nature into its macroeconomic models, in recognition of the impact of natural capital degradation on economic growth and employment generation (World Bank, 2025).
- The Financial Stability Board (FSB), an international body that monitors and makes recommendations about the global financial system, acknowledges that nature-related risks may have profound effects on both the real economy and the financial system (FSB, 2024).
- The Asian Infrastructure Investment Bank recommends that nature should be viewed as infrastructure, and indicates that identifying risks associated with losing nature is crucial, as unsustainable extraction of nature's resources for economic development jeopardizes future growth (AIIB, 2023).

Accordingly, governments and major financial institutions are increasingly beginning to assess nature-related financial and economic risks, alongside climate risk; to conduct nature stress tests, analogous to climate stress tests; and to formulate risk reduction and mitigation strategies.[46]

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 assessed would negatively affect economic growth, reducing UK GDP by 6-12% 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.

A recent nature stress test, conducted on the banking systems of five African countries, found that if current practices continue, nature-related physical risks could be substantial for some sectors, with significant macroeconomic implications (McKinsey, 2024). For example, risks such as declining pollinator populations, soil quality and water availability could decrease the net present value of profits in Ghana's agricultural sector by more than 50% by 2050 (McKinsey,

[46] These include: the Network for Greening the Financial System; the private sector international Taskforce on Nature-Related Financial Disclosures; the global insurance and re/insurance industry; the central banks of EU, France and the Netherlands; and ten multilateral investment banks (AIIB, 2023; NGFS, 2024; UN, 2021).

2024). Key overall risk drivers were water scarcity, water pollution, soil degradation, loss of pollinator populations and ecosystem degradation. Financial risks were consistently found to be lowest under an orderly transition aligned with the goals of the Global Biodiversity Framework.

Coral reef die-off

Coral reefs provide critical habitat and support for at least 25% of all marine life, including 4,000 species of fish (Global Coral Reef Monitoring Network, GCRMN, 2021). They provide extensive ecosystem services to humans; they are the source of approximately 25% of the world's fish catch, providing food for over 1 billion people, and they also provide carbon sequestration and oxygen generation services and coastal protection against storms, floods and land erosion (Findlay *et al.*, 2025). There are an estimated 6 million coral reef fishers worldwide, and coral reef fisheries are valued at $US 6.8 billion per year, producing an average annual yield of 1.4 million tonnes of seafood (GCRMN, 2021). In some areas, such as west Africa and the Pacific islands, fish from coral reefs are the primary source of animal protein (Eddy *et al.*, 2021). The total value of goods and services provided by coral reefs is estimated at US$2.7 trillion per year (GCRMN, 2021).

However, coral cover and its ability to provide ecosystem services has declined by over 50% since the 1950s, as coral reefs have died due to ocean acidification caused by increased CO2 uptake, and to rising ocean temperatures and heat extremes, compounded by overfishing, pollution and habitat destruction (Eddy *et al.*, 2021; Findlay *et al.*, 2025). The resulting losses have been linked to steep declines in fish and shellfish populations, and in ecosystem services. Coral reef associated fish catches peaked in 2002 at 2.3 million tons and have subsequently been declining despite increasing fishing effort; catch per unit of fishing effort in coral reef areas has fallen by 60% since 1950 and by 45% since 1990 (Eddy *et al.*, 2021).

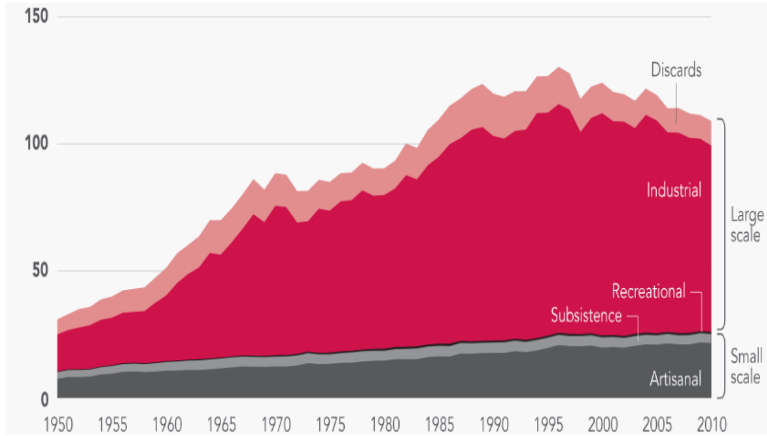
In the Caribbean, an area highly dependent on fish consumption, a more than 50% loss of coral reef habitat since 1970 has led to sharp declines in commercial fish populations. Fish catches in the area dropped by 40% between 2000 and 2019 (Vignati, 2021).

Depleted fish and shellfish populations

It is estimated that global predatory fish biomass today is approximately 90% below preindustrial levels, depleted by a frequently repeated pattern of overfishing to the point that fish stocks crashed (Myers and Worm, 2003). Myers and Worm found that industrialized fisheries have typically reduced local fish population biomass by 80% within 15 years (Myers and Worm, 2003). Depleted fish stocks of course reduce fishery productivity, as trawlers have to travel further and use more intensive methods to sustain catches.

After decades of growth, global wild fish catches peaked in the 1990s and have since been declining, with implications for food security; wild fish catches dropped by 13% between 1996 and 2010 (Chart 43) (Pauly and Zeller, 2016). Subsequent increases in fishery yields have relied on aquaculture, which requires significant inputs for feeding and stock maintenance.

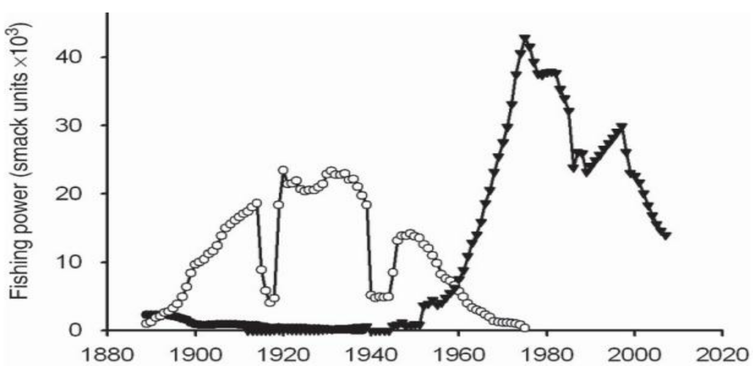
Chart 43: Global fish catches, 1950-2010 (millions of metric tons)



Source: Pauly and Zeller (2016)

In the UK, Thurstan *et al.* documented changes in fishery productivity spanning the transition from sail-powered fleets to steam and subsequently diesel, 1889 to 2007, by assessing landings of groundfish (e.g. haddock, cod) against measures of the fishing power of the domestic fleet (Thurstan *et al.*, 2010). They found that, outside the two wartime periods, total landings rose rapidly from the late 19th century to the mid 20th century, due to fleet growth, technological progress and range expansion. After World War II, however, landings slid into a long-term decline, despite heavy fleet investments that raised total fishing power tenfold (Chart 44).

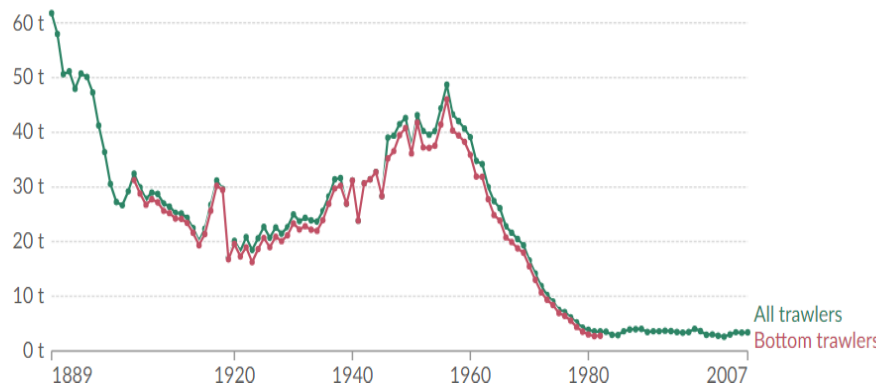
Chart 44: UK groundfish landings and total fishing power of British trawlers, 1889-2007



Open circles are total groundfish landings; dark line is estimated total fishing power of British trawlers. Source: Thurstan et al. (2010)

The study found that fishery productivity – landings per unit of fishing power – more than doubled between the 1920s and the 1950s, as investments in more powerful trawlers yielded higher landings (Chart 45). However, after the 1950s fishery productivity declined precipitously; by 2007 it had been reduced by 94%: "For every unit of fishing power expended today, bottom trawlers land little more than one seventeenth of the catches in the late nineteenth century." (Thurstan *et al.*, 2010).

Chart 45: Productivity of British bottom fishery, 1889- 2007
Landings (tonnes) per unit of fishing power



Source: Thurstan et al. (2010)

For some species the productivity decline was even greater – over 99% for haddock and halibut, to a total catch close to zero by 2007. The authors conclude that in many cases today's fisheries "are sustained by population of species that should be considered commercially extinct." (Thurstan *et al.*, 2010).

The experience of the UK groundfishery clearly demonstrates a case of natural capital depletion in which even intensive investments in physical capital could only temporarily offset productivity losses – and this at the expense of further depleting fish stocks, resulting in greater long-term losses in productivity. Because natural capital is not included in production functions, these productivity losses would be registered as declines in multifactor productivity – thereby obscuring the role of fish stock depletion, and the key point that it was a lack of fish, not fishing capacity, that became the key production constraint.

On the other side of the Atlantic, a strikingly similar story played out in the rich fishing area centred around Newfoundland's Grand Banks (Text Box 3).

More recently, in the western Baltic, fishery productivity declined precipitously as catches of cod – the main resource species – declined by 90% between the late 1990s and 2018; subsequently the size of the fishing fleet dropped by 50% (Mollman *et al.*, 2021). Scientists concluded that the western Baltic cod population had collapsed due to overfishing, with low prospects for recovery in part because of climate-induced warming of the sea. Western Baltic herring are experiencing similar pressures. Accordingly, the entire western Baltic fishery is now considered endangered, as fish populations are no longer sufficient to support the present fleet size (Mollman *et al.*, 2021).

Factors other than overfishing have also had significant effects on marine fish populations (Text Box 4). Marine heat waves have increased significantly in frequency and duration over the past half century, with associated losses of kelp forests and coral reefs, mass mortality of shellfish and other marine invertebrates, declines in fish populations and associated economic impacts on both wild fish catches and aquaculture, sometimes resulting in fisheries closures (Oliver *et al.*, 2018). Globally, heat waves have resulted in reduced aquaculture production as well as lower wild fish catches, due to disease outbreaks, harmful algal blooms and reduced growth rates (Free *et al.*, 2023).

Federal fisheries disasters and fishery closures were declared in the US as the result of the negative impact of the 2014-2016 marine heatwave on cod, crab, sardine and salmon stocks, resulting in over $141 million in relief payments to impacted fishers and processers (Free *et al.*, 2023). In Alaska, sudden and severe declines in the Pacific cod population beginning in 2017 caused the complete closure of the U.S. federal Pacific cod fishery in 2020, and its subsequent reopening with greatly reduced catch limits, as the cod population has shown few signs of recovery (Free *et al.*, 2023). And in the aftermath of the heat wave, some runs of Chinook salmon were down to the lowest levels in over thirty years. (Free *et al.*, 2023).

Similarly, a marine heatwave off western Australia in 2010-2011 tipped kelp forests into fields of algae and turf grass that have subsequently failed to recover, reducing stocks of abalone and rock lobster and their respective yields (Free *et al.*, 2023).

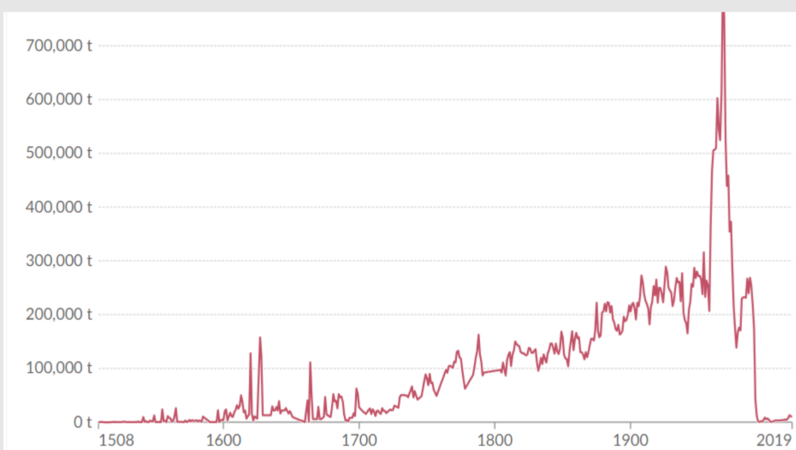
Text Box 3. The Canadian east coast fishery: a case study in natural capital depletion

The rich fishing waters of the northwest Atlantic were well known to Europeans, including Vikings and Basques, for centuries. When Cabot arrived on the eastern coast of what is now Canada in 1497, he described seas 'swarming with fish' that could be caught simply by dropping baskets over the side of boats (Frankopan, 2023). By the time of Champlain, in the early 1600s, French fishermen were bringing back between 100,000 and 200,000 tonnes of cod a year to France in good years (Fischer, 2009; Schijns et al., 2021). Catches of between 100,000 and 300,000 tonnes per year were sustained from the mid-1700s until the 1950s.

The advent of industrial bottom trawl fishing boats in the late 1950s nearly quadrupled the annual cod catch over the course of a single decade, from 207,000 tonnes in 1958 to a peak of 810,000 tonnes in 1968 (Schijns et al., 2021). However, cod catches subsequently plummeted and by 1990 were down to less than half of the peak – 395,000 tonnes, out of a total of over 1M tonnes of fish landings. In 1992, faced with crashing stocks, the Canadian government abruptly closed the commercial cod fishery. It was estimated that by that time only .33% of the original cod population remained; Atlantic cod has been on the IUCN Red List of species at risk of extinction since 1996 (Rose, 2004). The commercial cod fishery – previously a mainstay of the Atlantic provinces' economy – remained closed for over thirty years, although some recreational and indigenous fishing was permitted, with a very limited reopening in 2024. Following the closure of the cod fishery, many east coast fishers were left, literally, with stranded assets in the form of fishing boats that no longer yielded a living.

So the powerhouse east coast fishery, which reeled in over 1M tonnes of fish in 1990, was reduced to just 14% of that catch by 2023 (DFO, 2025). Cod landings, which had been the fishery's core, dropped to only 3.8% of pre-closure yields. However, the entire fishery has been decimated, in a cascading impact. Catches of all fish other than cod – including herring, the second most important fish – were down by 80% in 2023 compared with 1990 levels. Only shellfish landings have risen since the 1990s.

Chart 46: Five centuries of cod catches in eastern Canada (tonnes)



Source: Schjins et al. (2021)

Text Box 4: Interactions among climate change, sea stars, kelp forests and fisheries

Sea star wasting disease has been described as the largest ever marine epidemic, causing mass mortality among twenty species of sea stars along the west coast of North America since 2013, with some species declining by 90-95%. Over 6 billion sunflower sea stars – one of the largest sea stars – have died; 87% of this keystone species has disappeared in its northern range, and it is considered functionally extinct in its southern ranges (Prentice et al., 2025). The cause of the disease has been identified as a bacterium whose prevalence correlates positively with ocean temperatures; scientists therefore believe that climate change has materially contributed to its rapid spread (Prentice et al., 2025). The impact of this epidemic was exacerbated by two marine heat waves along the west coast, in 2014-2016 and 2021, that also triggered an unprecedented harmful algal bloom resulting in coastwide shellfish fishery closures (Free et al., 2023).

In consequence of the mass sea star die-off, sea urchins, which are starfish prey, experienced unchecked population growth. As sea urchins consume kelp, their proliferation, together with climate-induced ocean warming, decimated kelp forests, reducing them by 95% along much of the west coast (UNEP, 2023d). Kelp forests harbour a rich diversity of marine life, but many have been replaced since 2013 by “urchin barrens” – areas inhabited by sea urchins and little else. Transformations of kelp forests into urchin barrens are difficult to recover from and can persist for decades (UNEP 2023d) – an example of how ecosystem collapse is frequently effectively irreversible.

Kelp forests sequester significant amounts of carbon (4.9 MT per year), cycle nitrogen and provide habitat for fish and marine mammals. The value of these services has been assessed at $111,000 / hectare per year, or a global total of $500 billion (Eger et al., 2023). Kelp forests also buffer coastlines from storms.

The NA west coast forests harbour multiple fish and shellfish species including seabass, pollack, salmon, herring, rockfish, lobster, crab and abalone, with associated fisheries valued at $1-33 million per species per region per year (UNEP, 2023d). However, as habitat has declined with the disappearance of the kelp forests, there have been cascading impacts on fish and shellfish populations and the fisheries they support.

In British Columbia, commercial fish landings have dropped significantly since the starfish epidemic swept through that coastal area in 2015 and 2016, destroying most of the coastal kelp forest. Landings of pelagic fish – primarily salmon, herring and tuna – known to shelter in the forests, fell by 70% between 2016 and 2023, while groundfish landings fell by 50% between 2018 and 2023 (FOC, 2025). The value of the B.C. commercial fishery declined by 37%, or $108M, between 2018 and 2023 (FOC, 2025).

Similarly, in northern California, the red abalone population is estimated to have declined by 80% between 2013 and 2017 as its key food source, kelp, vanished, resulting in the closure of the $44 million / year recreational abalone fishery in 2018. (The commercial abalone fishery had already been closed in California in 1997 due to previous steep population declines.) (Reid et al., 2016; Rogers-Bennett & Catton, 2019).

Freshwater fisheries have also been under severe pressure. Populations of migratory fish – which comprise the majority of freshwater catch – have declined by an average of 81% since 1970 due to habitat alteration, overfishing, pollution and climate change (WWF, 2024) with proportionate impacts on catches by inland fisheries and subsistence fishers.

Significant freshwater population declines had already occurred prior to 1970 due to related pressures. For example, Lake Ontario Atlantic salmon – once a dietary staple and the basis of a thriving commercial fishery employing thousands of people – began to decline in the mid-1800s and ceased to exist over 100 years ago (COSEWIC, 2006).[47] Their decline was attributed to overfishing, and to damming of spawning rivers and related habitat destruction. Attempts to re-establish self-reproducing Atlantic salmon in the lake have failed, in another example of the frequent irreversibility of ecological collapse; the Lake Ontario Atlantic salmon population was designated extirpated in 2006. Worldwide, similar declines in Atlantic salmon populations have occurred, in tandem with declines in the number of rivers supporting spawning runs (COSEWIC, 2006).

Fish populations have also been adversely affected by chemical exposures, negatively impacting related fisheries. In Japan, runoffs from rapidly increasing use of neonicotinoid pesticides in agriculture after 1992 led to the collapse of two commercially harvested freshwater fish species, smelts and eels, in a Japanese lake (Yamamuro *et al.*, 2019).[48] High concentrations of the pesticides, at levels known to be toxic for aquatic invertebrates, severely reduced the abundance of two species that serve as key food sources for fish – zooplankton (by 83%) and midges (by 100%). This consequently resulted in large reductions in commercial catches of smelts (91%) and eels (74%). The study authors concluded that their findings could likely be extrapolated to the entire country; i.e. that nationwide decreases in Japanese freshwater fishery yields since 1992 were likely attributable to the impacts of extensive neonicotinoid use. They also concluded that high global prevalence of neonicotinoids in agriculture means that this effect is probably widespread worldwide (Yamamuro *et al.*, 2019).

Globally, the FAO has documented that the percentage of global fish stocks that had dropped below biologically sustainable levels rose from 10% in 1974 to 35% in 2019 (FAO, 2022b).

The World Bank included blue natural capital – marine capture fisheries and mangroves – in its natural capital valuation for the first time in 2021. The Bank found that the global asset value of fisheries collapsed by 83% between 1995 and 2018 due to depletion of fish stocks (World Bank,

[47] In the early 1800s, salmon in Lake Ontario tributaries were described as being so abundant that they were "thrown out with a shovel and even with the hand" (COSEWIC, 2006). The abundance of Lake Ontario salmon is viewed as an important factor that attracted both indigenous and settler populations to the shores of Lake Ontario.
[48] Neonicotinoid pesticides are the most heavily used pesticide class, accounting for over one quarter of the global pesticide market of $US 5.3B in 2024. A number of studies that have shown that they have severe negative effects on pollinators, particularly bees, and other nontarget species. The European Union banned its use in 2018, following one such study from the European Food Safety Authority (EFSA, 2018). The US Environmental Protection Agency concluded in 2022 that neonicotinoids likely adversely affect the great majority of 1,700 endangered and threatened species and 800 critical habitats in the US (US EPA, 2022).

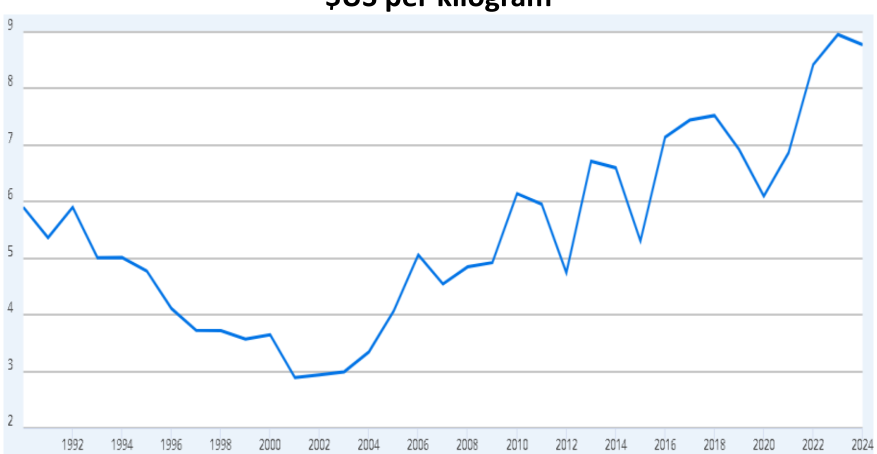
2021). This contributed to the value of blue natural capital falling in half over this period, while the fisheries share of blue capital declined from 85% to 27%.

While fisheries account for a relatively small share of GDP – especially after the crash of fishing stocks -- their demise may have disproportionately large impact on local and regional economies via dynamic effects. Communities for which fishing formed the economic base may no longer be viable, with knock-on effects in multiple other industries.

Production has increasingly shifted towards farmed fish to meet rising demand, as marine capture fish has fallen. However, a range of sustainability and health concerns have been raised with regard to farmed fish, including their impact on wild fish populations and the presence of much higher toxin levels (e.g. PCBs) in farmed fish that would constitute a cost to public health. Further, subsistence fishing typically relies on wild fish capture, so the disappearance of wild fish stocks significantly affects some of the most vulnerable communities and individuals that rely on them as a food source; in many developing countries, fish is the major animal protein source that rural people can access and afford (Pauly and Zeller, 2016). Pauly and Zeller stress that the importance of subsistence fishing for food security in developing countries cannot be overemphasized (Pauly and Zeller, 2016).

Unsurprisingly, worldwide declines in fish populations and catches have been reflected in global fish prices, which have tripled since the early 2000s (Chart 47).

Chart 47: Global price of fish, 1990-2024
$US per kilogram



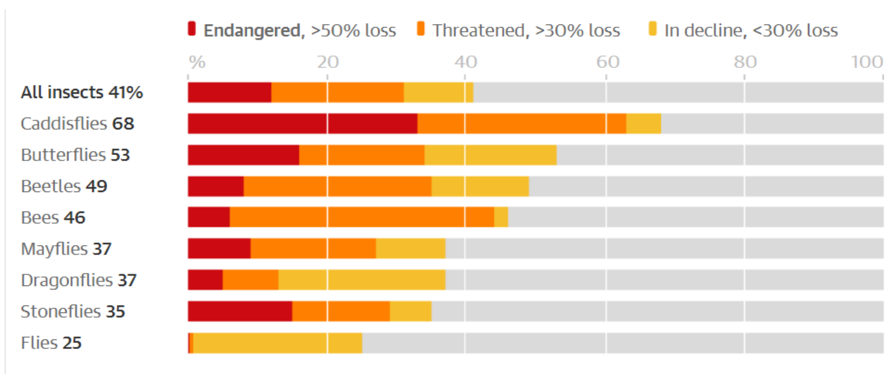
Source: IMF via Federal Reserve Bank of St. Louis (FRED), 2025

Pollinator loss and agricultural productivity

Pollination is a critically important ecosystem service necessary for the reproduction of 87% of all plant species and three quarters of agricultural crops, representing 35% of global crop production by volume and including most vegetables and fruits, many nuts and seeds as well as key cash crops such as coffee and cocoa (Goulson, 2019; IPBES, 2016; Reilly, 2020; Schowalter, 2022). Global reliance on pollinator-dependent crops has increased over the past several decades, and the value of agricultural pollination services has been assessed at 1% of global GDP (Reilly, 2020).[49] The vast majority of pollinator species are wild (IPBES, 2016) and a number of studies have found that wild pollinators have a stronger positive effect on crop yields than managed pollinators (Reilly, 2020). Crop yield and quality depend on both the abundance and diversity of -pollinators (IPBES, 2016).

However, large declines in wild pollinator populations have been documented worldwide over many decades, due largely to habitat destruction and fragmentation, the impact of agricultural chemicals such as pesticides, other pollution, and climate change (Cibotti *et al.*, 2025; Goulson, 2019; IPBES, 2016; Sanchez-Bayo & Wyckhuys, 2019; Schowalter, 2022). Globally, over half (53%) of butterfly and moth species, and 46% of bee species declined between 2010 and 2019 (Chart 48) many to the point that they are threatened with extinction – 44% of bee species and 34% of butterfly and moth species are in this category (Sanchez-Bayo & Wyckhuys, 2019). Further, 15% of bee species and 11% of butterfly and moth species have gone regionally extinct within the past fifty years. (Sanchez-Bayo & Wyckhuys, 2019). Many birds also act as pollinators, and over half (53%) of bird populations have been declining (Finn *et al.*, 2023).

Chart 48: Percentage of insect species in decline, 2010-2019



Source: F. Sanchez-Bayo & Wyckhuys (2019) and D. Carrington (2019)

A number of studies have shown that agricultural yields decline when pollinators or pollinator diversity decline (IPBES, 2016). Accordingly, as pollinator numbers have fallen, pollinator-dependent crops have experienced slower growth in yield per hectare than pollinator-independent crops, and have displayed less stability in yield per acre (IPBES, 2016). Studies have also confirmed that for a number of crops a lack of pollinators is acting directly to restrict yields – a phenomenon known as 'pollinator limitation' (Reilly, 2020). These findings demonstrate how pollinator loss translates into reduced agricultural productivity. The IPBES estimated that 5-8% of global crop production (valued at between US $235 - $577 billion in $ 2015) was at risk as a result of pollinator loss (IPBES, 2019).

[49] In the US alone, the value was assessed at $29 billion in 2010 by Krishna Ramanujan (Thomas et al., 2017).

As wild pollinators decline, with related impacts on crop yields, agricultural producers turn to pollination services (such as managed hives) that are often less effective than wild pollinators and are always more costly, with associated productivity impacts.

Consider the case of vanilla, currently one of the most expensive food ingredients in the world. Vanilla orchids can be pollinated by only one type of bee, the melipona bee, which is now nearly extinct in its native Mexico due to deforestation, pesticides and invasive species. Accordingly, nearly all commercial vanilla production has largely shifted to costly and labour-intensive hand pollination, with associated lower productivity and significantly higher prices (VanillaPura, 2025).

Deforestation

Forests cover 31% of the Earth's land surface and support 80% of terrestrial biodiversity; they provide habitat for 90% of amphibian species, 75% of bird species and 68% of mammal species (FAO, 2022a). In addition, they provide numerous ecosystem services: carbon storage; rainfall regulation; water capture and filtration; air quality regulation; soil stabilization and conservation; soil quality maintenance; protection against storms, floods and landslides; temperature regulation; and reduction in disease outbreaks (Almeida *et al.*, 2024). Forests contain 662 billion tonnes of carbon, more than half the global carbon stock, in soil and vegetation (FAO, 2022a).

Accordingly, deforestation leads to the loss of many of these ecosystem services and the benefits they provide to humans, with sometimes significant negative economic impacts that can offset economic benefits accruing from forest harvest and clearing.

Forest ecosystems have experienced extensive loss and degradation over time. One fifth of global forests, approximately 10M square kilometres, have been lost since 1900, with 42% of that area lost between 1990 and 2020 (FAO, 2022a). Large-scale commodity agriculture has been one of the largest drivers of recent deforestation, with large tracts of forest cleared in the Amazon to produce beef and soybeans, and in southeast Asia to produce palm oil. Wildfires have become a growing source of forest loss and now account for nearly half of annual forest loss (MacCarthy *et al.*, 2025).

As a result of deforestation, some tropical forests which were previously major carbon sinks now emit more carbon than they capture (Almeida *et al.*, 2024). Deforestation in the Amazon rainforest – which has the greatest concentration of biodiversity in the world – may be approaching a tipping point that could transform it from carbon sink to net emitter, and even trigger the dieback of the entire forest (Araujo and Mourão, 2023). Approximately 20% of the Amazon forest's original area has already been lost, while a further 20% has been degraded, meaning that it has lost vegetation and is therefore less able to provide critical ecosystem services (Araujo & Mourão, 2023).

Forests are central to the water cycle, absorbing rainwater from the soil and returning it to the atmosphere via transpiration, effectively recycling the rain. Globally, "green water" from land-based evapotranspiration, driven largely by forests, accounts for nearly half (45%) of all precipitation on land, with much higher percentages in some locations, e.g. Congo (87%), Central African Republic (88%) and Mongolia (95%) (Damania *et al.*, 2025; De Petrillo *et al.*, 2025).[50] Consequently, loss of natural forests reduces regional rainfall, dries out soils and accordingly reduces crop yields.

Nearly half of Amazon rainfall is generated by evapotranspiration, also called 'flying rivers' (Araujo and Mourão, 2023; Damania *et al.*, 2025; Xu *et al.*, 2022). Deforestation has interrupted this water cycle, reducing the availability of water in the atmosphere and in the forest, driving further forest degradation, and thereby accelerating forest loss in a domino effect. (Araujo & Mourao, 2023; Xu *et al.*, 2022). Climate-forest model analysis has found that for every 100 trees deforested, an average of 22 additional trees die in consequence due to lack of water (Araujo & Mourão, 2023). In addition, increased water stress makes forests more susceptible to fire; the frequency of Amazon wildfires has risen 20-28-fold in the past two decades (Cunningham *et al.*, 2024).

Water is a major input to agriculture, power generation and industrial processes. Water scarcity therefore constrains growth; it has been found to be correlated with lower productivity, GDP growth and investment (Frost *et al.*, 2025).

Forests support agriculture downstream by capturing and storing water, then releasing it gradually, thereby sustaining moisture in agricultural soils. Deforestation accordingly reduces crop yields by drying out soils and reducing water availability. Deforestation was recently estimated to have reduced global agricultural GDP by 8%, equivalent to $379 billion, in this way (Damania *et al.*, 2025).

Deforestation-induced rainfall loss in the Amazon area between 2001 and 2020 – amounting to 20-25% reductions in affected regions – and related depletion of freshwater resources, is estimated to be responsible for reducing regional hydropower production by approximately 8%, and for reducing agricultural productivity by approximately 0.6% per year, at a cost of $3-11 billion per year in GDP losses in these countries (Araujo & Hector, 2024; Damania *et al.*, 2025). The three countries most affected by this rainfall loss were: Paraguay (average annual loss of 0.8 percentage points of GDP growth between 2001 and 2020); Bolivia (0.5 pps); and Brazil (0.3 pps) (Damania *et al.*, 2025).

In Africa, deforestation along the West African coast has disrupted rainfall recycling, contributing to desertification in the Sahel area and related loss of productive land.

Upstream forest cover helps buffer the adverse economic impacts of droughts, supporting soil moisture during rainfall deficits. Estimates indicate that forests neutralize about half of the potential economic growth losses from rainfall deficits in this manner (Damania *et al.*, 2025); this represents another ecosystem and economic service that is lost when deforestation occurs.

[50] Approximately 65% of the world's freshwater stocks are held in soil and vegetation, compared with just 35% in rivers, lakes and glaciers (Damania et al., 2025).

Conversion of forests to permanent agricultural land is often accompanied by progressive soil degradation and related loss of land productivity, as has occurred in western Kenya (Almeida *et al.*, 2024).

Tropical deforestation has been linked to significant numbers of excess deaths due to associated local warming. As moisture from evapotranspiration has a strong local cooling effect, loss of tree cover can induce increases in local temperatures (Xu *et al.*, 2022). A recent study found that deforestation alone drove an average of 0.45°C of warming in the tropics from 2001-20, accounting for two thirds of total warming in regions with tropical forest loss (Reddington *et al.*, 2025). This tropical deforestation exposed three quarters of local populations – 345 million people – to local warming as a result of loss of forest cover, in addition to that caused by global warming (Reddington *et al.*, 2025). The authors calculated that warming driven by deforestation caused an extra 28,000 heat-related deaths per year in Africa, South America and Asia over this period, accounting for over one third of total climate heat-related mortality in regions of tropical forest loss (Reddington *et al.*, 2025).

Productivity can also be directly affected by deforestation-induced warming. A study in Indonesia randomly assigned workers to forested and deforested settings and found that there was an 8% decrease in productivity in the hotter, deforested areas; cognitive performance was also worse in these areas (Damania *et al.*, 2025).

For example, a study in Indonesia that randomly assigned workers to forested and deforested settings revealed a 2.8°C difference in wet-bulb temperature and an 8.2% decrease in productivity in the hotter, deforested areas (Masuda *et al.* 2021). Cognitive performance was also worse in deforested settings (Masuda *et al.* 2020)

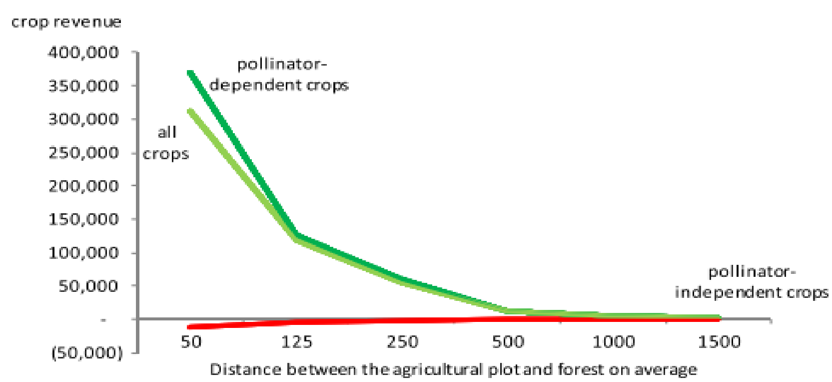
The role of forests in preserving the quality of watersheds has also been shown to significantly affect human capital via its effect on health, particularly among children. Diarrheal disease due to contaminated water is one of the leading causes of child mortality globally (Herrera *et al.*, 2017). A recent study, based on evidence from 46 countries, found that deforestation upstream affects water quality downstream, raising the incidence of diarrheal disease, nutritional deficiencies and stunted growth among young children, thereby affecting human capital development with subsequent productivity impacts (Damania *et al.*, 2023). A 1% decline in upstream forest cover around the time of birth was found to increase the probability of diarrheal disease in young children by 5.8%, and of growth stunting by 3.9% (Damania *et al.* 2023; Damania *et al.*, 2025).

Similarly, a study of health and nutrition outcomes among children in Malawi between 2000 and 2019 found that children living in areas with net forest cover loss were 19% less likely to have a diverse diet and 29% more likely to be Vitamin A deficient, a condition linked to higher incidence of malaria and vision problems (Johnson *et al.*, 2013).

Deforestation has also been linked to increased incidence of malaria, via increased human exposure to mosquito vectors, in numerous studies and in a wide range of locations.[51] In the -Amazon, a 4% increase in deforestation rates was associated with a 48% increase in malaria incidence (Olson *et al.*, 2010). In Indonesia, a 1% decline in forest cover was linked to a 10% rise in malaria cases (Damania *et al.*, 2025). And in Central America, a one standard deviation decrease in tree cover (0.05) was found to be associated with an increase of 0.13 in the number of cases of malaria per 1,000 inhabitants (Springborn *et al.*, 2022). The economic impacts of increased malaria incidence include premature mortality, medical costs, and school absenteeism. Studies have also linked deforestation to increased incidence of dengue fever and Ebola virus (Almeida *et al.*, 2024).

Forests provide critical habitat for many wild pollinators; in Tanzania, proximity to forests has been shown to contribute significantly to revenue from pollinator-dependent crops, especially for small farmers (Tibesigwa *et al.*, 2019). Deforestation over a seven-year period (2008-2013) was, accordingly, found to have directly reduced crop revenue for these farmers, by between 7% and 29% (Chart 49).

Chart 49: Forest contribution to crop revenue per acre (Tanzanian shillings) by distance from agricultural plot (metres)



Source: Tibesigwa et al., 2019

Declining vertebrate populations

Biodiversity has been found to have significant direct positive impacts on productivity and human capital and its decline, accordingly, to negatively affect productivity and human capital. Due to the high degree of interconnectivity in ecosystems, biodiversity declines and losses of key species have produced major economic and productivity impacts, sometimes through unexpected channels.

Bird and bat populations, both of which are declining, provide a number of direct services that improve agricultural productivity and/or human health. Bird and bat species provide significant agricultural services by consuming insects that otherwise damage crops. In Jamaica, birds have

[51] Malaria is a major cause of mortality in developing countries; in 2023 there were 263 million cases and 597 000 malaria deaths worldwide (WHO, 2024).

been found to perform a service valued at between $75 and $310 per hectare-year by eating crop-damaging insects on coffee farms (Thomas *et al.*, 2017).

Bats. In the US, approximately 13% of crops are destroyed by insects each year, and agricultural pest control activities provided by bats have been valued at between $US 4 and $US 53 billion per year (Frank, 2024). However, a recently emergent bat disease, white-nose syndrome, has killed approximately 90% of some North American bat populations since 2006, with mean mortality rates of 73% in infected populations (Frank, 2024). Frank examined the impact of these population declines in 245 US counties. He found that farmers in affected counties increased their use of insecticide by an average of 31% to compensate for the loss of bat services – an example of substitution of a human-made input for a natural input – and that crop revenue per square kilometre in these counties dropped by 29%. He evaluated total lost crop revenue and increased chemical expenditure at $US 26.9 B ($2017) for the affected counties over an 11-year period (2006-2017); the annual average of these losses corresponds to 1.3% of 2017 US crop revenue ($190B). He also found an 8% increase in infant mortality in affected counties in the years following detection of white-nose syndrome, translating into an additional 1,334 infant deaths, which he attributes to the detrimental health impacts of higher environmental pesticide exposures. Using the EPA's estimated value of a statistical life ($US 9.24 million $2017) he estimated the cost of this lost human potential and human capital at $US12.4 billion (Frank, 2024).

Sparrows. In China, a campaign to eradicate sparrows was launched in 1958, as part of the Four Pests Campaign, which aimed to eliminate rats, flies, mosquitoes and sparrows. Sparrows were targeted because they were believed to ruin harvests by consuming significant quantities of grain. However, their inclusion in the campaign failed to account for the significant benefit they provided to farmers by consuming large numbers of crop-damaging insects such as locusts and rice planthoppers. An estimated two billion sparrows were killed across China in 1959, driving the birds to near extinction in the country and leading to a boom in insect populations, with consequent large-scale crop damage from insect infestations, particularly in rice and wheat (Frank *et al.*, 2025; Frankopan, 2023). This was a significant contributing factor to China's Great Famine, believed to have been the largest famine in human history, and estimated to have killed 35 - 50 million people between 1959 and 1961 (Frankopan, 2023). Sparrow-suitable counties experienced both the largest reductions in rice and wheat production in 1960-1961, and the largest spikes in mortality (Frank *et al.*, 2025). Frank *et al.* calculated that sparrow killing accounted for one fifth (20%) of the reduction in national crop yield during the Great Famine and was directly responsible for nearly two million lives lost (Frank *et al.*, 2025).[52]

[52] In 1960, the Chinese government reversed the order to kill sparrows, in the face of evidence of its unintended impact. As sparrows had already become locally extinct in most of the country, 250,000 were reportedly imported from the USSR to reboot the population. Following this policy reversal, rice and wheat yields gradually returned to their former levels (Frank et al., 2025). A similar occurrence took place in Prussia in 1744 when Frederick the Great tried to eliminate sparrows but ended up with pest outbreaks and had to import sparrows from other countries to repopulate them.

Vultures. In India, vultures long provided an important sanitation service through their scavenging activities. However, their population dropped precipitously after 1993 following sharply increased use of a livestock drug that proved toxic to the birds. This population drop led to a 5% 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.

Amphibians. A disease (chytridiomycosis) caused by a fungal pathogen (Bd) emerged in the late 20th century, triggering an amphibian epidemic that resulted in a massive worldwide die-off, with the extinction or serious decline of hundreds of amphibian species. It has been described as the largest known loss of biodiversity due to a disease. Biologists have directly linked the disease's rapid spread to increased regional temperature variability and extreme weather events due to climate change, that reduced amphibian immune defences and increased their susceptibility to disease (Rohr and Raffel, 2010).

As amphibians consume large quantities of insects, their population losses typically result in increased insect abundance, including of mosquitoes that can transmit human diseases. A study analyzed the impact of chytridiomycosis in Costa Rica and Panama between 1980 and 2010 and found a causal link between waves of Bd-driven collapse of amphibians and extended large waves of increased human malaria incidence, with ensuing peak malaria incidence 70-90% above background rates (Springborn *et al.*, 2022). Increased human malaria incidence due to the onset of amphibian decline lasted for approximately a decade.

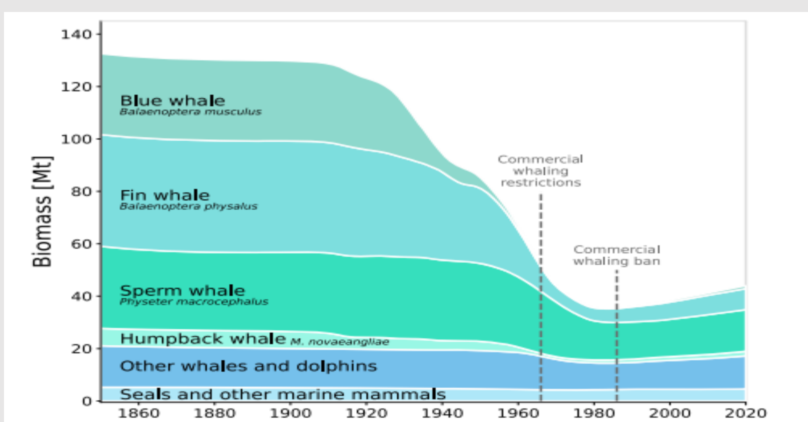
Other vertebrates*.* Work has been underway to assess the economic value of ecosystem services provided by numerous other animals, including sea otters, whales (Text Box 5), beavers, elephants and bison. This work demonstrates that the introduction or removal of a single species can have wide-reaching economic consequences. For example, studies have found that beaver-built wetlands can help landscapes retain water during drought periods, and can increase groundwater recharge tenfold in dry periods (Wang *et al.*, 2025).

Text Box 5. Whales: Impacts of population declines

Whales provide an excellent example of how failure to account for natural capital – particularly the external benefits of ecosystem services – can result in severely suboptimal market decisions.* Whales play a highly important role in the marine carbon cycle in two significant ways. First, their movement and effluents significantly boost production of phytoplankton, which contributes at least half of the oxygen in the atmosphere, and accounts for about 40% of carbon dioxide capture (37 billion tons per year) (Chami, 2019). Secondly, their large bodies, which contain an enormous amount of carbon, sink to the bottom of the ocean when they die, sequestering for centuries an average 33 tons of CO2 per great whale. Chami *et al.* accordingly calculated that, on the basis of a social cost of carbon of only US$70 per ton, the social value of an average living blue whale would be US$6 million, compared with a current market value of its products of approximately $90,000. (Current estimates of the social cost of carbon are considerably higher, e.g. $190 per ton by the U.S. Environmental Protection Agency and some in excess of $1,500, which would raise the social value of whales still further.) These factors were not, of course, taken into account during the era of large-scale whaling, which resulted in total whale numbers dropping from 4-5 million to approximately 1.3 million today. Blue whale numbers dropped from approximately 240,000 to today's figure of around 7,000.

Accordingly, the ecosystem services provided by whales are currently much lower than they were at their pre-whaling population, when they captured 1.7 billion tons of CO2 annually. As there are many substitutes for the commercial products yielded by a dead whale, this indicates that failing to account for the value of natural capital – including the external benefit of ecosystem services such as carbon capture - yielded a highly suboptimal outcome, with far fewer whales left in the ocean. Chami *et al.* conclude that the ecosystem services provided by living whales are sufficiently large to justify significant investments in measures to boost their populations.

Chart 50: Global biomass of whales and other marine mammals, 1850-2020



Source: Greenspoon et al. (2025)

** This section draws on analysis by Chami et al. (2019) and Dasgupta (2021).*

c) Productivity impacts: depletion of soil and sub-soil resources

Groundwater depletion

Globally, groundwater is often heavily used for agricultural irrigation, particularly to support the cultivation of water-intensive crops such as rice and cotton in dry areas. Reliance on groundwater irrigation increased from the mid-20th century on with improvements to pumping and irrigation technologies, permitting agricultural production where it would otherwise have been impossible due to arid climates or limited surface-water supplies. (Hrozencik, 2023).

In India, groundwater accounts for 60% of the water used for irrigation, and groundwater irrigation supports the production of over half of domestic caloric consumption (Bhattarai, 2021). Since the 1980s, when groundwater pumps began to proliferate, the number of groundwater structures has quadrupled to 20 million; however, over the same period, groundwater levels have dropped by an average of over 8 metres (Bhattarai, 2021), indicating that withdrawals have significantly exceeded the rate of recharge. Bhattarai found that declining groundwater levels in India were associated with significant reductions in yield and production for winter crops of wheat, rice, sorghum and maize (Bhattarai, 2021). Specifically, his study found that at the national level each metre of decline in groundwater depth was associated with a 1%-3% decline in mean yields for winter crops, with the largest effect (3%) on winter rice. Yield declines, where other inputs are unchanged, are equivalent to MFP declines. As groundwater levels have dropped by more than 8 metres over the past forty years, this suggests that declining groundwater levels may have acted to reduce the productivity of winter grain agriculture in India by between 8% and 24%.

In the United States, groundwater accounts for 95% of the nation's freshwater resources, and over one third of agricultural acreage currently relies at least partly on groundwater irrigation (Hrozencik, 2023). However, over half of all US wells have had consistently falling water levels since 1940, including those accessing some of the most economically important aquifers (Hrozencik, 2023; Rojanasakul *et al.*, 2023). The impacts of heavy usage have been amplified by drier conditions related to climate change, which both reduce water availability from above-ground sources and also slow the rate of aquifer replenishment. Contamination of aquifers by nitrates, salinity and heavy metals, impairing water quality used to grow food crops, has also been a concern.

This groundwater loss has had wide-ranging impacts, reducing crop yields and compromising the viability of agriculture in some areas. In Kansas, corn yields have plummeted from 170 bushels per acre to less than 100 (i.e. by over 40%) over the past twenty years as groundwater availability has declined, and the major aquifer underlying the state can no longer support industrial-scale agriculture (Rojanasakul *et al.*, 2023). This situation has prompted exploration of innovations to improve irrigation systems and plant genetics. However, physical capital and technology cannot substitute for water. Bill Golden, a professor of agricultural economics at Kansas State University, concluded: “The loss of water is going to outpace the gain of technology. Eventually we are going to lose.” (Rojanasakul *et al.*, 2023).

Groundwater depletion also affects home and industrial water consumption, such as in the fast-growing city of Phoenix, Arizona, where permission to build new houses was suspended because there was not enough groundwater to supply them (Rojanasakul *et al.*, 2023). It can result in higher pumping costs, raising the cost of water for all purposes, and it can also cause saltwater intrusion into freshwater aquifers, eventually contaminating those aquifers (Jasechko *et al.*, 2024). In some cases, groundwater depletion has necessitated costly pipelines to transport large volumes of water over distances, e.g. China's South-to-North Water Transfer Project and India's National River Linking Project (Famiglietti, 2024).

Aquifer depletion has also caused subsiding land levels and sinkholes, damaging buildings and infrastructure and raising vulnerability to flood risks and rising sea levels, as well as permanently reducing aquifer storage capacity in some instances (Jasechko *et al.*, 2024; Rojanasakul, 2024; Davydzenka, 2024). Davydzenka determined that over 6.3 million square kilometres of global land inhabited by nearly 2 billion persons is experiencing significant subsidence; that groundwater withdrawals are the most important predictor of land subsidence; and that the rate of subsidence is positively correlated to the intensity of groundwater withdrawals (Davydzenka, 2024). Subsiding land is increasingly found near densely urban, agricultural and industrial areas with high groundwater demand (Davydzenka, 2024). In Iran groundwater depletion, due to drought and high water demand, resulted in such acute water shortages and land subsidence in Tehran that the President announced this year that the nation's capital will have to be moved to a different location (Basilio, 2025).

Finally, groundwater depletion can lead to drying up of wetlands and rivers, with implications for river transportation, fish stocks and above-ground sources of water supply as well as ecosystems (Doll, 2014).

Soil degradation and erosion

The imbalance between accelerated soil loss on agricultural land and slow natural rates of soil formation has been observed for many decades. 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% in global crop yields, or a 20% cumulative global decline (FAO, 2015). Accordingly, soil degradation and erosion affect not just short-term agricultural productivity but also long-term yields. Approximately 1.7 billion people worldwide live in areas where crop yields are falling because of human-induced land degradation (FAO, 2025).

Soil erosion causes huge losses of soil nutrients – an estimated 38-68 MT of nitrogen and phosphorous annually – which then need to be replaced through fertilization at significant cost, estimated in 2015 at $US 110-200B (FAO, 2015a). In regions where economic resources are insufficient to undertake intensive fertilization, erosion results in ongoing soil depletion.

In the EU, the economic cost of soil degradation was estimated in 2019 to be in the order of tens of billions of euros annually (FAO, 2021). In Africa, it is estimated that 3% of GDP is lost annually from soil and nutrient depletion of croplands (McKinsey, 2024). Soil remediation can be costly and slow.

Soil degradation and erosion are also of concern due to loss of the ecosystem services it provides; soil is the largest carbon reservoir after the oceans, and accounts for an estimated 25% of global biodiversity (FAO, 2021). Forests and wetlands and their soils are huge reservoirs of carbon, and forest soils store approximately the same amount of carbon as the forest's living biomass (FAO, 2015a). Accordingly, deforestation and the conversion of wetlands to other purposes results in large losses of soil carbon. Deforestation is estimated to be responsible for one quarter of total global losses of soil carbon (FAO, 2015a). When forest is converted to cropland, approximately 25-30% of the organic carbon in the soil is lost in temperate regions, and up to 50% in the tropics (FAO, 2015). While loss of soil organic carbon can occur very rapidly, the rate of re-carbonization of soil is extremely slow (FAO, 2015a).

Conversion of agricultural or natural land for urbanization, industrialization or road construction typically results in extensive 'soil sealing', or the permanent covering of the soil surface with impermeable material. This produces irreversible soil change and often permanently reduces the available stock of arable land:

> "Soil sealing is in practice equivalent to total soil loss – virtually all services and functions are lost except the carrying capacity as a platform for supporting infrastructure. The main negative impacts on ecosystem services include: virtually total loss of food and fibre production; a significant decrease or total loss of the soil's water retention, neutralization and purification capacities; the loss of the carbon sequestration capacity; and a significant decrease in the ability to provide (micro) climate regulation." (FAO, 2015a).

Approximately 0.5% of the earth's surface is affected by soil sealing, and expanding cities often seal areas of high-quality soil in densely populated areas (FAO, 2015a).

Former war zones have also rendered large areas of land unusable, particularly where minefields exist. Approximately 110 million mines and other unexploded ordnance in 64 countries prevent or impair productive land use (FAO, 2015a), as well as extracting an ongoing toll in death and injuries.

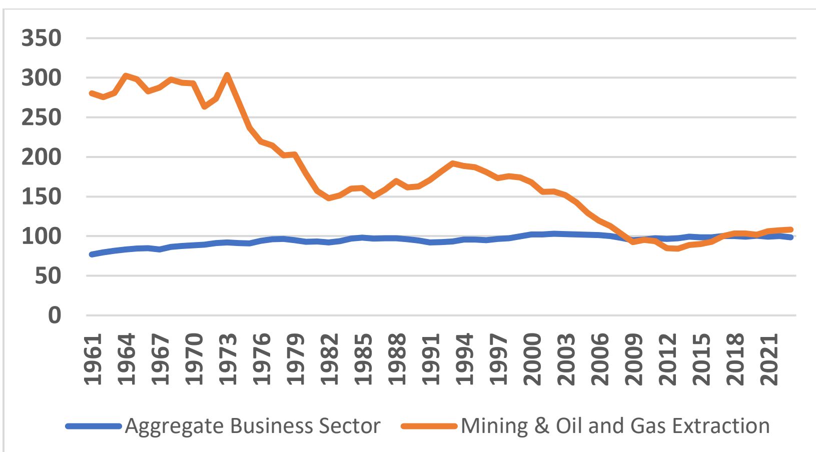
Soil contamination affects agricultural productivity by reducing crop yields and by reducing the stock of arable land that can be safely cultivated (FAO, 2015). It affects large areas of land globally and therefore represents a significant constraint on agricultural production. In China, contamination of one fifth of all farmland by heavy metals is estimated to reduce national food production by 10 million tons per year (FAO, 2015). Contamination from nuclear sources is severe in some places, resulting in arable land being taken out of production for very long periods, as is the case in Chernobyl, the Fukushima area and the Marshall Islands (FAO, 2015a).

Depletion of mineral 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 61% over six decades – from an index of 280 in 1961 to 108 in 2021 (2017 = 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 (Chart 51). If MFP growth in mining and oil and gas had equalled that in the rest of the business sector from 1961 to 2023, cumulative growth in Canadian business sector MFP would have been 15% higher (author's calculations).

Chart 51: Canadian Multifactor Productivity Index, Aggregate Business Sector and Mining and Oil and Gas Extraction, 1961-2023 (2017 = 100)



Source: Statistics Canada (2025c)

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 to wards oil sands (Loertscher and Pujolas, 2023).

Sharpe and Waslander (2014) found, however, that, over the shorter oil boom period from 2000 to 2012, declining productivity in the oil and gas sector had only a relatively small impact on overall business sector labour productivity growth, due to the positive reallocation effect of the large influx of workers into this high productivity sector. It is unclear to what extent this effect might prevail outside of the oil boom period.

d) Productivity impacts: Pollution, waste and contamination

The World Bank has found that approximately 90% of the global population lives with degraded land, or polluted air, or unsafe water (Damania *et al.*, 2025). In low-income countries, about 80% of people live with all three environmental stressors (Damania *et al.*, 2025).

A recent global study found that pollution was responsible for 9 million deaths in 2019, or one in six deaths worldwide (Fuller *et al.*, 2022). Deaths from outdoor air pollution and toxic chemical pollution (e.g. lead) had risen by 7% since 2015 and by 66% since 2000 (Fuller *et al.*, 2022).

Air pollution

Air pollution significantly affects productivity via a wide range of negative health impacts that reduce the stock of human capital via illness, disability and premature death, simultaneously lowering the return on investments in skills and education (Brauer *et al.*, 2024; Health Effects Institute, 2020). These health impacts include disease, disability and premature death from respiratory illness, strokes, heart attacks, cancer, diabetes, damage to childhood IQ, higher incidence of low birthweight and preterm births, and increased overall mortality (Health Effects Institute, 2020).[53]

99% of the world's population is exposed to pollution levels exceeding World Health Organization guidelines (5 micrograms per cubic metre of PM 2.5 particles) (World Bank, 2025a). Fine particulate air pollution (PM2.5), produced by fossil fuel combustion and wildfires, contributes to two thirds of air pollution deaths (Health Effects Institute, 2020); ozone and nitrogen dioxide are other factors.

Rates of global population exposure to dangerous levels of outdoor air pollution have risen, and are highest in India, China, west Africa and eastern Europe (Brauer *et al.*, 2024; Health Effects Institute, 2022). Between 1990 and 2021, the proportion of the global population exposed to hazardous levels of particulate matter rose by 43%, while exposure to hazardous levels of ozone rose by 45% (Health Effects Institute, 2022). Death rates from outdoor (PM) pollution have accordingly also risen, by 39% between 1990 and 2019 (World Bank, 2025a).[54]

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% of all life years lost (Brauer *et al.*, 2024).[55] It is the fourth leading global risk factor for early death and accounts for more than one in nine deaths

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[53] Indoor air pollution is also a major cause of illness and mortality, particularly in emerging economies, but is not discussed here as its impact on natural capital is less clear than that of outdoor air pollution.
[54] Global death rates from indoor pollution fell by 65% over the same period. Outdoor pollution now accounts for two thirds of all air pollution deaths (World Bank, 2021a).
[55] This metric, disability-adjusted life years (DALYs), sums years of life lost due to premature death and years lived with disability.

worldwide, 5.7 million annually, reducing average global life expectancy by 1.9 years (Greenstone *et al.*, 2025; Health Effects Institute, 2020). The economic damages associated with these health impacts have been assessed at $US 6 trillion per year, equal to 4.6% of global GDP, from poor health outcomes, premature mortality, productivity loss and cognitive impacts (World Bank, 2025a).

Illness and disability caused by air pollution lower worker productivity by increasing absences from work, thereby reducing average output per worker. The OECD found that in 2010 air pollution resulted in 1% of global workdays being lost, restricted activity days or partially restricted activity days (OECD, 2016). In 2016, outdoor air pollution was found to have negatively impacted labour productivity in all regions and sectors, slowing global economic growth by 0.1 percentage points in that year (OECD, 2016).

- In Europe, PM 2.5 concentrations of 1 microgram per cubic metre (µg/m3) lead to a 0.8% decrease in real GDP due to increased absenteeism, lowering productivity (Damania *et al.*, 2025).
- In India, a 1 µg/m3 increase in air pollution was found to depress GDP growth by 0.7 percentage points (Damania *et al.*, 2025).

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% 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.*, 2022a, b)**.**

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 in 2006 reduced same-year crop yields for wheat (by 10%), rice (2.5%), soybeans (2.2%) and maize (0.3%), lowering total national agricultural output by 1.1% (Miao *et al.*, 2017). Some previous studies found much higher crop losses attributable to ozone for rice (10-15%), soybeans (16%) and maize (22%) (Miao *et al.*, 2017).

Water pollution

Water pollution affects productivity primarily via its impacts on human health and mortality.

Overall surface water quality has decreased at the global level, causing the cost of treating water to rise, together with the health costs associated with contaminated water (IPBES, 2020).

One quarter of the global population, over 2 billion people, drink water contaminated with feces, which is linked to diarrheal disease and transmission of diseases such as cholera, dysentery and typhoid (World Bank, 2025; Damania *et al.*, 2025). Unsafe drinking water, combined with inadequate sanitation and poor hygiene, are responsible for 1.4 million deaths each year, and 74 million disability-adjusted life-years (DALYs) lost, representing 2.5% of all global deaths and 2.9% of global DALYs (Hay *et al.*, 2025).

Unsafe water is a leading risk factor for death and disease among children under the age of five. Diarrheal disease is the second leading cause of death among children in this age group, responsible for 361,000 deaths annually (Herrera *et al.*, 2017).

Further, contaminated water reduces labour productivity and impairs child development. These economic costs have been estimated as ranging from $3 to $49 per capita, depending on the country (Damania *et al.*, 2025)

A recent study found that only one third of the population of 135 low and middle-income countries had access to safe water in 2020 (Greenwood *et al.*, 2024). The highest population proportions without safe water were found in countries in sub-Saharan Africa, Oceania, southeastern Asia, and Latin America and the Caribbean.

The number of freshwater bodies with high enough water quality for untreated human consumption has fallen over time, with a corresponding decline in the numbers of people relying on untreated surface drinking water sources, estimated at 122 million globally in 2022 (IPBES, 2020; WHO, 2022).

Plastic pollution

Plastic pollution affects productivity via its impacts on human health, as well as via its effects on marine environments. Plastics have become so pervasive in the environment that humans now regularly consume and inhale microplastics and nanoplastics or absorb them through their skin. Microplastics and nanoplastics have been detected in a wide range of foodstuffs and beverages, and microplastic particles have been found in a majority of global samples of tap water (81%) and bottled water (93%) (Yee *et al.*, 2021). The average person ingests or inhales an annual total in the range of 100,000 microparticles (UNEP, 2021; Yee *et al.*, 2021) Microplastic particles eventually break down into nanoparticles, which are absorbed even more easily into human tissues.

Many plastic chemicals are known to be damaging to human and animal health (UNEP, 2021). Of 13,000 plastic-related chemicals, only 7,000 have been screened for hazardous properties; of these, 3,200 have been identified as of concern due to hazardous properties including carcinogenicity, mutagenicity, reproductive toxicity, endocrine disruption, and ecotoxicity (UNEP, 2023a).

Accumulated plastic has been found in tissues throughout the human body, with associated significant health impacts (Campen *et al.*, 2024; UNEP, 2021). Plastic particles have been found to accumulate in the lungs, blood vessels, liver, kidneys, placenta and semen, with the highest concentrations in brain tissue; tissue concentrations have increased over time (Campen *et al.*, 2024; UNEP, 2021).[56] While the scale of health effects is not yet known, exposure to plastics has been linked to a wide range of human health impacts including: cancer; cardiovascular disease;

[56] Microplastic concentrations were 10-20 times higher in brains than in other organs; the 24 brain samples examined in one study were an average of 0.5% plastic by weight (Campen et al., 2024).

respiratory disease; diabetes and other metabolic diseases; nervous system damage; reduced IQ and impaired learning and memory; reduced birth weight; thyroid disease; inflammation; and reduced fertility (UNEP, 2021). This broad range of health effects from a pollutant which is so prevalent in the environment can be expected to exert a significant, if as yet unmeasured, toll on human capital and labour via its effects on illness, disability and mortality, with repercussions on productivity.

Plastic debris has also been found in the digestive system of many forms of marine life, including all turtle species and half of seabird and marine mammal species sampled (UNEP, 2021). Plastic litter is known to kill large numbers of marine mammals, turtles, birds and fish each year via ingestion, entanglement, strangulation or abrasion, and to have sub-lethal effects on many others (Deloitte, 2019; UNEP, 2021). Abandoned or discarded fishing gear – often called "ghost gear" – constitutes about 10% of ocean plastic, and is particularly lethal; it is estimated to kill 300,000 whales, dolphins and porpoises annually, as well as many more seabirds, other marine mammals and invertebrates (WWF, 2020b).

Marine plastic litter and waste, including ghost gear, also causes significant mortality to fish and shellfish stocks, thereby affecting the productivity of commercial fisheries (UNEP, 2021). A Deloitte study estimated global economic losses from marine plastic pollution in 2018 at $6-19 billion ($US), including loss of revenue from fisheries, aquaculture and marine tourism, as well as the cost of cleanup of coastlines, waterways, marinas and ports (Deloitte, 2019). This estimate does not include the likely substantial costs of damage to natural capital and the associated degradation of ecosystem goods and services.

Other chemicals

Persistent organic pollutants (POPs) are present in a wide range of chemicals and consumer products, including flame retardants and non-stick pans.[57] They persist environmentally and biologically and often bioaccumulate. They have been detected worldwide in human and animal tissues (Brind'Amour, 2024). They are highly toxic and have been linked to numerous adverse health effects including cancer, neurological damage and disruption of the endocrine, reproductive and immune systems (UNEP, 2025b).

In the US, 97% of Americans have PFAS compounds in their bodily fluids and PFAS have widely contaminated drinking water systems (Brind'Amour, 2024). In 2023, 3M and three companies with ties to DuPont agreed to pay over $12 billion, following class action lawsuits, to compensate hundreds of public water providers in the US for the costs of cleaning up PFAS contamination in water supplies (Perkins, 2023)

In Canada, PFAS have been detected in groundwater in 87 federal sites, and in the drinking water of a number of communities (White & Jones, 2025). The British Columbia government launched a class action lawsuit in 2024 against 12 manufacturers of the chemical, citing

[57] Persistent organic pollutants (POPs) are chemicals that include polybrominated diphenyl ethers (PBDEs), per- and polyfluoroalkyl substances (PFASs), polychlorinated biphenyls (PCBs), and organochlorine (OC) pesticides.

widespread contamination of drinking water systems that poses “significant threats to human health for centuries” (Chiang & Shen, 2024).

Radiation

Radiation from multiple sources has been linked to significant health impacts to humans and ecosystems. Compensation paid to human victims of radiation provides a partial costing of these damages.

Radiation from atomic weapons testing, and related uranium mining, processing and transportation, has been linked to chronic renal disease, twenty types of cancer and five respiratory diseases (Szymendera, 2024). Between 1945 and 2006, 2,053 nuclear tests were conducted worldwide. Over half of these (1,054) were conducted by the United States; 100 of these were atmospheric tests, resulting in radioactive material being released into the atmosphere (Szymendera, 2024).[58] Due to high cancer rates among those participating in and close to these tests, the Radiation Exposure Compensation Act was passed by the US government in 1990, providing benefits of $50,000 to $100,000 per person to eligible persons who developed related diseases. Between 1990 and 2024, when program authorization expired, compensation totalling $2.6 billion was paid to 41,000 persons who were on-site participants, “downwinders” from the Nevada site, or uranium workers (Szymendera, 2024).[59] A proposed broadening of the program, never passed, that would have widened eligibility criteria and raised compensation payments, was costed by the Congressional Budget Office at $147 billion over ten years (Alvarez, 2024). In addition, as of 2024, 140,000 nuclear weapons workers had been awarded $24.4 billion in compensation and medical bill payments for illness and death due to radiation exposure, under the Energy Employee Occupational Illness Program Compensation Act, passed in 2000 (Alvarez, 2024).

Nuclear reactors have been another source of radiation. As of 2016, 448 nuclear power reactors were being operated in 30 countries; a further 141 reactors had been shut down, of which only 20 had been fully dismantled (IAEA, 2022). The most significant radiation exposures from nuclear reactors have occurred following accidents resulting in meltdowns – most notably Chernobyl, Fukushima and Three Mile Island.

The Fukushima nuclear accident in Japan was triggered by an earthquake and subsequent tsunami in 2011, resulting in meltdowns and severe core damage in three of the six reactors, and release of hydrogen and radioactive materials. Over 100,000 people were displaced and remain unable to return to their homes, and the cleanup and decommissioning process is expected to take 30-40 years (Barnard, 2018). The cost of the Fukushima accident has been estimated at $US 200-300 billion, or 3-5% of Japanese GDP in 2011, including: compensation for evacuees, decontamination, reactor decommissioning, generating replacement power; and export and tourism losses (Barnard, 2018; Committee on Lessons Learned from the Fukushima

[58] Of the 1,054 US atomic weapons tests between 1945 and 1992, the vast majority were at the Nevada Test Site (928) or Pacific Ocean islands (106).
[59] This represents an approval rate of 75% of all claims filed (Szymendera, 2024).

Nuclear Accident, 2014). However, at least one estimate has placed the cost at over $US 800 billion (Barnard, 2018).

After the 1979 meltdown at Three Mile Island, a Columbia University team found that newly diagnosed cancer cases within a 10-mile radius of the plant had increased by 64% in the five following years, yielding 1,100 excess cases. This increase was linked in subsequent analysis to radioactive releases from the plant (Alvarez, 2024).

8. Conclusion

Implications

The previous section has documented how pervasive natural capital declines are exerting significant negative impacts on productivity in every major economic sector worldwide. In case after case and sector after sector, environmental degradation – with associated declines in natural capital and the goods and services it provides – has direct and significant causal links to declines in productivity and output. This evidence provides robust support for the argument made here that, in aggregate, these impacts have reached sufficient cumulative magnitude in recent decades to exert substantial and consistent downward pressure on MFP and labour productivity growth.

Because natural capital data and accounts are still early in their developmental phase and are not yet integrated into national economic accounts, the prevailing economic framework often does not enable direct attribution of declining aggregate national productivity growth to declines in aggregate natural capital. However, it is implausible that such significant, extensive and repeated cumulative negative impacts have not translated into reduced overall productivity growth. These impacts are directly visible in reduced MFP and labour productivity growth over the past several decades in advanced economies and, more recently, in emerging and developing ones.

Indeed, natural capital declines may have been the primary cause of this declining productivity growth. However, our current economic framework lacks the capacity to either validate or disprove this theory; this suggests that we need an improved framework.

Neoclassical economists have traditionally viewed production and hence productivity as functions of produced capital, labour or human capital, and technology and innovation. Enormous effort has been directed to analyzing the nature of the interactions among these factors. However, the fundamental role of nature in providing largely free services has not been accounted for in standard productivity analyses or in the national accounts from which they are derived. When conventional economic accounts omit natural capital and therefore understate its role in affecting economic outcomes, they also overstate the role of other inputs in economic production and outcomes. The considerable explanatory power of changes in natural capital stocks has generally been overlooked in both productivity and growth analyses.

Because economists over the past century have generally ignored the natural foundations of economies, natural capital been largely invisible in economic indicators. It has been unpriced, undervalued, and therefore overused, to the point of depletion; natural capital declines have not led to rising prices signalling increased scarcity. It has also been overexploited, in part, because ownership is often public, meaning losses are widely dispersed, while significant gains accrue to individual producers.[60]

Our current economic models were largely developed at a time when nature was viewed as abundant and physical capital as scarce. Accordingly, the role of nature in economic production was largely ignored. However, nature has now become a relatively scarce and, indeed, limiting factor of production as natural capital stocks have eroded, but it is still being treated as effectively limitless in our analytical frameworks.

Consequently, we are currently overvaluing our total capital stock by failing to account for natural capital depletion. We are not as rich as we think we are – our measure of total productive capacity has been increasingly overestimated. The work undertaken by UNEP shows that increases in produced and human capital in recent decades have been more than offset by declining natural capital.

On a broader level, the analysis presented here contradicts the widely accepted notion of a tradeoff between environmental and economic objectives. Instead, it finds that damage to the environment is ultimately deeply damaging to the economy, and that investments in the economy's natural capital foundation are supportive of economic prosperity.

Future directions

In 2025, the global economy is situated in a world in which the 1.5°C warming mark has been breached for three consecutive years, weather systems are becoming increasingly unpredictable and dangerous, and drought and deforestation have reduced the planet's natural carbon sink capacity. Global fossil CO2 emissions are projected to increase by 1.1% in 2025 to a new high (Friedlingstein *et al.*, 2025a). Forecasts indicate that warming of 2.8°C can be expected by the end of this century under current policies, with possible tipping points encountered below 2°C for coral reef die-off (already underway), polar ice sheet collapse, die-back of the Amazon rainforest, and collapse of the Atlantic Meridional Overturning Current (Lenton *et al.*, 2025; UNEP, 2025a).

The previous sections demonstrated the widespread negative productivity impacts of natural capital degradation to date. There is now broad consensus that continued climate change will have significant future impacts on economic and productivity growth, with most recent modelling exercises forecasting an intensification of negative economic outcomes under scenarios where climate change is not kept within tight limits. For example:

- 1.2% annual losses in global GDP from 2021 through 2100 under a 1-2.6°C warming scenario; annual GDP losses of 3.2% through 2100 under a 2-4.5°C scenario, compared to one without climate change (Lepore and Fernando, 2023);

[60] In the absence of any significant direct cost for appropriating natural capital, its exploitation often gives rise to significant rents, i.e. returns in excess of what is required to provide supply at a given level of demand. The existence of these rents will induce continued market activity by suppliers, and will draw in new suppliers. Economic theory tells us that economic rents will be collected until they have been driven down to zero.

- Annual world GDP declines by 27% by 2050 under a business-as-usual scenario of 3°C by 2100, compared to a scenario without climate change; and by 48% by 2100, reflecting accumulated productivity losses that eventually reach 39% (Bilal and Kanzig, 2024).
- Annual global GDP losses reaching 40% by 2100 under a high-emissions scenario (5-8.5°C) compared with a low-emissions scenario (1-2.6°C) including global weather (Neal, Newell & Pitman, 2025).
- Annual global GDP losses of 31% by 2100 under a current policies scenario, with tail risks of up to 50% (Network for Greening the Financial System, 2024).
- Annual global GDP losses of 11-14% by 2050 based on a trajectory of 2-2.6°C warming (Swiss Re, 2021).

Stern and Stiglitz have opined: "Without stronger climate action, current growth rates cannot be sustained. … In the medium to longer run, there is no high-carbon growth story: the effects of unmanaged climate change are so severe that they will very likely derail any (misguided) attempt at high-carbon growth. The only long-run growth trajectory is a green trajectory." (Stern and Stiglitz, 2023)

Assessments of future economic losses due to climate change have generally risen over time as more robust underlying parameters have been incorporated into Integrated Assessment Models.[61] As these assessed losses have risen, there is increasing consensus that the costs of not addressing climate change and nature loss exceed the costs of taking the necessary steps to address them (Deloitte, 2022; IPCC, 2023; NGFS, 2025).

All sectors are generally projected to experience productivity losses, but agriculture is usually assessed as the most vulnerable; one study estimates that agricultural productivity would fall by 10-20% in most regions of the world over the balance of this century under either a 1-2.6°C or 2-4.5° warming scenario (Lepore and Fernando, 2023). A separate study projects rising global incidences of crop failures, with failure probabilities even under a 'moderate' 1.5-2°C scenario rising to up to 4.5 times higher by 2030 than in 2021, and up to 25 times higher by 2050; this corresponds to a 50% crop failure rate for rice, maize and soybeans by 2050 and a 42% failure rate for wheat (Caparas *et al.*, 2021).

A continued slowing in global agricultural TFP growth would jeopardize the ability of agricultural production to keep pace with global population growth (Fuglie, 2021; Fuglie *et al.*, 2024).

Recent scenario analyses of economic impacts from loss of ecosystem services (e.g. pollinator decline, deforestation, flood protection), some of which assess compound climate and nature

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[61] Many economic assessments to date based on Integrated Assessment Models have likely significantly underestimated the likely impacts of climate change, for reasons including: unrealistic ceteris paribus parameters in a highly dynamic context; unduly high discount rates; failure to account adequately for climate risks (including discontinuities, irreversibility, feedback loops, tipping points, and exponential rather than linear change); failure to account adequately for other significant risks such as widespread crop failures, climate-related biodiversity loss, large-scale climate migration, or the potential for climate-related armed conflict; modelling changes in average temperature and precipitation but not higher incidences of extreme weather; modelling local rather than global climate phenomena; and applying a general equilibrium framework to a situation that inherently reflects disequilibrium. Adaptation is a factor that could potentially act to reduce some impacts.

risk or pollution-induced biodiversity risk, are also projecting very significant sectoral, national and global GDP declines from such losses (Ceglar *et al.*, 2025; Johnson *et al*., 2021; O'Donnell *et al.*, 2025; Ranger *et al.*, 2023).

Population pressures are a major component of environmental stressors, with UN-projected global population peaking at 10.3 billion by the mid-2080s, up from the current 8.3 billion (UN, 2024). Fertility rates are currently below replacement levels (2.1) in much of the world, but remain high in many lower income countries and in those where women's human rights are not well established.[62] Even with a very low global fertility rate of 0.5, world population would peak near 9 billion by mid-century, declining to 6 billion by 2100 (UN, 2022).

Our economic framework needs to align with environmental objectives. New economic thinking is increasingly calling for the integration of valuations of natural capital into our economic frameworks, accounts and policies. However, this is happening very slowly. Economists and scientists remain largely in silos, and most economic analyses still make no direct mention of factors related to natural capital.

The addition of comprehensive capital accounts, including natural capital, to our economic toolkit provides a useful complement to GDP measurements that can help to address some of the deficiencies of GDP as a measure of economic progress. These deficiencies include the exclusion of external costs and benefits, of nonmarket products and services, and the fact that GDP counts "throughput" as a positive, meaning that deadweight economic costs raise GDP even when they do not improve standard of living and may in fact be associated with net loss of natural capital assets.

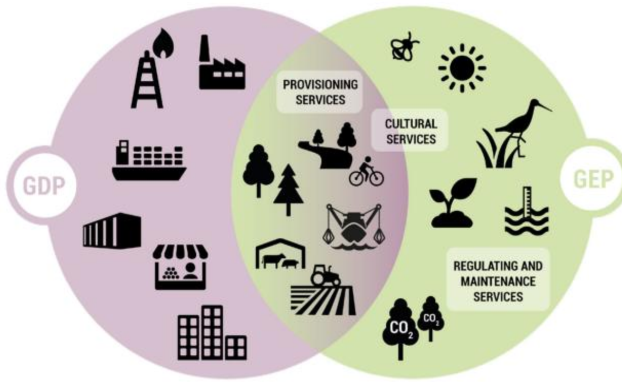
Based on the analysis and evidence presented here, a key element of any productivity strategy, whether national or global, must be the reversal of the long-term decline in natural capital. If natural capital erosion has become a key factor limiting and even reducing economic prosperity, the corollary is a need to invest in its preservation and restoration. Extensive work has been undertaken in international arenas to develop roadmaps towards sustainability, with several key international frameworks in place and others under development:

1. **The United Nations (UN) System of Environmental Economic Accounting (SEEA)** underpins the natural capital assessments produced by the UNEP, the World Bank and the OECD. It integrates economic and environmental data into a common framework that includes measures of stocks of environmental assets and flows of ecosystem services (UN, 2020). The framework was adopted by the UN Statistical Commission in 2021, and over 90 countries are now implementing national SEEA accounts incorporating ecosystem accounting, from a zero base in 2013. Many of these efforts are still in the early, rudimentary stages, however, and much further work will be needed to ensure methodological consensus, develop comprehensive and internationally comparable measures, and expand their usage as a tool of economic analysis and decision-making.

[62] The fertility rate is the average number of children born per woman throughout her childbearing years.

In addition to providing the underlying framework for the measures of natural capital explored in this report, the SEEA underpins measures of green GDP, or environmentally-adjusted domestic product, such as that used by the OECD in its environmentally-adjusted productivity measures. Significant work has also been undertaken over the past decade to develop a measure of Gross Ecosystem Product (GEP) that aggregates the economic value of ecosystem services into a single monetary metric that overlaps with and is complementary to GDP (Ouyang *et al.*, 2020; Rokicki *et al.*, 2024; Van Alphen *et al.*, 2024; Zheng *et al.*, 2023) (Chart 52).

Chart 52: Overlapping areas of GDP and GEP



Source: Van Alphen et al. (2024)

2. **The Paris Agreement** on climate change was adopted by 196 parties at the 2015 UN Climate Change Conference (COP21), with the goal of holding the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the increase to 1.5°C. However, national policies implemented as of 2025 do not come close to achieving the rapid and deep GHG emission reductions needed to achieve these targets, according to the IPCC.

Fossil fuel subsidies totalling at least $7 trillion, or 7.1% of global GDP, remain in place, including explicit subsidies of $1.3 trillion and implicit subsidies of $5.7 trillion from underpricing (Black, Liu, Parry and Vernon, 2023). Fossil fuel exploration is proceeding and new development projects being approved, despite the assertion of the International Energy Association that no new investment or development in oil, gas or coal is warranted under an energy sector pathway to net zero by 2050 (IEA, 2021). Nevertheless, renewable energy production is accelerating, and global investments in clean energy are expected to total $2.2 trillion in 2025, double the $1.1 trillion anticipated for fossil fuels (IEA, 2025b).

3. **The Montreal-Kunming Global Biodiversity Framework** was adopted by nearly 200 nations in 2023, with the objective of catalyzing international action to halt and reverse biodiversity loss. The framework sets out long-term goals for 2050 and action-oriented targets for 2030, including: integrating biodiversity into national policies; phasing out incentives harmful to biodiversity; increasing financial resources and incentives for conservation and biodiversity plans; and setting aside 30% of the world's land and water areas as protected zones (UNEP, 2022a). This effort is clearly still in the early stages of implementation, but is progressing. As of

the end of 2024, 119 countries had submitted national targets, which will be the basis for national reports due in February 2026, and 44 countries had submitted revised national biodiversity strategies and action plans.

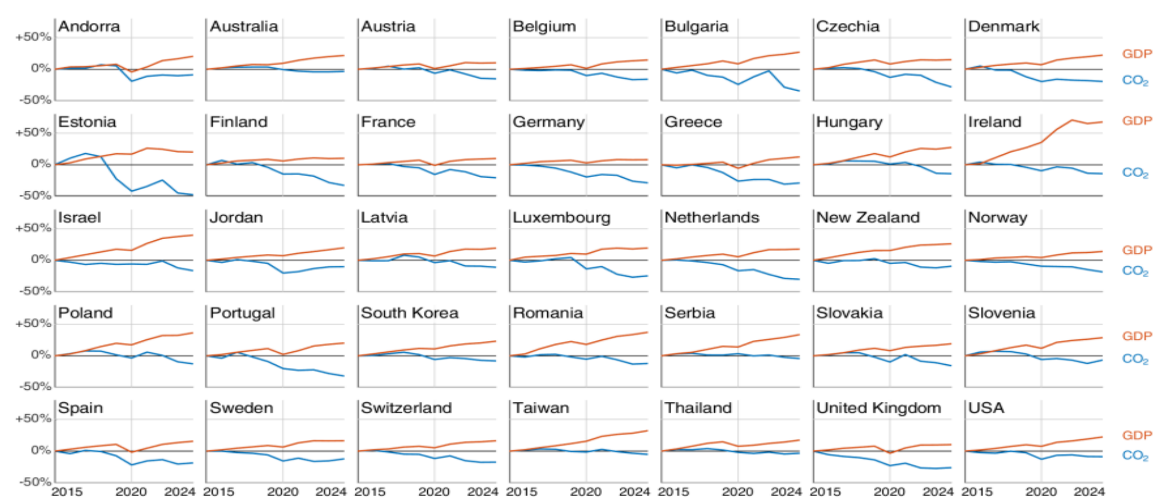
4. **The High Seas Treaty**. In September 2025 the ratification threshold was reached for January 2026 implementation of a new treaty on Marine Biological Biodiversity of Areas Beyond National Jurisdiction, commonly known as the High Seas Treaty. It provides for shared governance of the oceans and allows for the establishment of marine protected areas outside national boundaries; at present, only about 1% of the high seas are protected.

As well, international negotiations have been underway since March 2022 to develop a legally binding international instrument on plastic pollution that would address the full life cycle of plastic from design and production through disposal (UNEP, 2024b). However, these negotiations are currently stalled, largely due to opposition to production cuts from oil-producing nations.

There remain highly divergent views on how best to sustain high living standards without further damage to the natural environment. This is epitomized by the debate between those who espouse a “green growth” approach based on the concept that technological innovation can overcome the challenge of exhaustible resources – and accordingly that economic growth can be decoupled from GHG emissions and natural capital damage – and those who argue that unlimited growth is impossible on a finite planet, and that some limitations to growth are therefore necessary to achieve sustainability (e.g. Jackson, 2017; Raworth, 2017)

Recent analysis indicates that while the association between GDP per capita and CO2 emissions per capita is weakening over time, it remains positive globally. While 49 mostly high-income countries have decoupled emissions from economic growth, 115 have not, including most African, American, and Asian countries (Freire-Gonzalez *et al.*, 2024). Over the 2015-2024 period, 35 countries show simultaneous declining CO2 emissions and rising GDP (Chart 53).

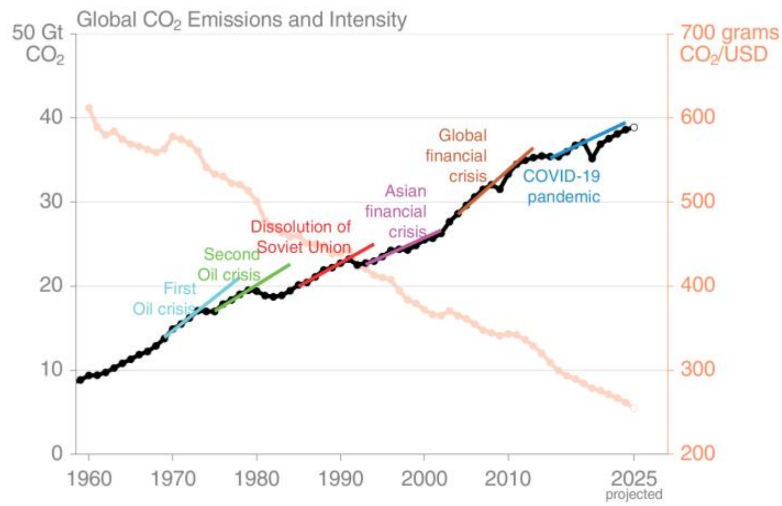
Chart 53: Countries with declining CO2 emissions and rising GDP, 2015-2024



Source: Friedlingstein et al. (2025); Global Carbon Project (2025)

The downward global trend in the emissions intensity of GDP has not been sufficient to offset rising emissions due to economic growth (Chart 54).

Chart 54: Declining global CO2 emissions intensity of GDP and rising global CO2 emissions, 1960-2025



Source: Friedlingstein et al. (2025); Global Carbon Project (2025)

An evolving toolkit of policy measures continues to be developed. With respect to climate change, carbon pricing is the single tool most widely endorsed by economists to achieve economically efficient emissions reductions (Canada's Ecofiscal Commission, 2019; Nordhaus, 2018; Stern, 2006). However, only 28% of annual global GHG emissions were covered by a carbon pricing instrument in 2025, and carbon prices generally remain much lower than required to substantively mitigate climate change (World Bank, 2025). Recent assessments of the carbon prices required to contain climate change vary significantly, but have been rising over time (Nordhaus, 2018; World Bank, 2024a). The World Bank estimated in 2024 that 2030 carbon price levels consistent with limiting warming to 1.5°C were $US 226-385 /t (World Bank, 2024a). Consumer resistance to carbon pricing has been a significant obstacle, however, as in Canada where, despite a relatively modest and largely revenue neutral carbon levy, consumer opposition forced the 2025 revocation of the federal consumer carbon tax, in place since 2019. A number of observers have therefore concluded that climate targets can most reliably be achieved via a combination of carbon pricing, regulation and fiscal incentives including subsidies.

A wide range of other policy measures can be directed towards enhancing sustainability and the preservation of natural capital. These include eliminating perverse incentives, such as by pricing negative externalities; putting in place incentives or legislated requirements for conservation and sustainable practices; and regulation. Some countries are putting in place biodiversity requirements, as mandated under the Montreal-Kunming Framework, such as the biodiversity net gain requirement for new construction projects under recent British legislation (Weston, 2024). At the administrative level, requirements that every government policy be assessed through a sustainability lens are another tool.

Internationally, green financial instruments and nature-related asset classes and trading arrangements are being developed by actors such as development agencies and multilateral development banks, with tools such as green bonds increasingly being used to secure financing for sustainability initiatives. Other tools include debt-for-nature swaps, payment for ecosystem services, biodiversity credits and offsets, sustainability-linked loans and incorporating natural capital valuation into cost-benefit analyses. Nature stress tests are increasingly being utilized by governments and financial institutions, alongside climate stress tests, and nature is being integrated into some key macroeconomic models, such as that used by the World Bank (World Bank, 2025c). Large corporations, particularly those based in Europe, are also beginning to integrate nature-related risks in to decision-making (Risilience, 2025).

Climate-related policies need to be underpinned by economic analyses that incorporate an appropriate social cost for greenhouse gases. Estimates of the social cost of carbon have risen steeply in recent years, as the economic costs of climate change have been more clearly delineated, and lower discount rates have progressively been incorporated.[63]

Proceeding towards greater sustainability will require moving toward a circular economy model that minimizes both resource extraction and waste generation. In 2019, only 9% of the materials used in manufacturing and construction were secondary, or recycled (UNEP, 2024a). However, one analysis estimated that the current economic structure allows for circularity of only 30%-40% and that pushing the circularity rate beyond this range would therefore require more fundamental structural changes in global production and consumption systems (Haas *et al.*, 2015).

Key issues to be resolved are those of national boundaries and appropriate time horizons. Global trade and economic integration mean that natural capital depletion incurred in economic production will often generate both income and consumption in locations far from the site of natural capital losses. Similarly, investments in natural capital may incur immediate costs that are borne by nations or individuals, but generate benefits that are shared globally and extend over the longer term, resulting in disincentives to act even where aggregate benefits greatly exceed aggregate costs.

Looking forward, the energy transition away from fossil fuels towards carbon-free energy sources offers an avenue for sustained improvement in living standards that does not compromise natural capital.[64] The transition should yield not insignificant productivity

[63] The social cost of a tonne of carbon is defined as the present net value of harm to society globally from its emission; which is equivalent to the global net benefit of reducing carbon emissions by a tonne (US EPA, 2023). As recently as 2017, the UK figure for the social cost of carbon was only $5.44 per tonne of CO2, and the US EPA figure was $36 per tonne (Thomas et al., 2017). The EPA raised its estimate to $190 in 2023, while some more recent estimates have been in excess of $1,500 per tonne (e.g. Bilal and Kanzig, 2024).

[64] The International Energy Agency calculated that in 2023 clean energy accounted for 10% of global GDP growth, and fully one third of GDP growth in the EU. It found that global clean energy investment had grown by 40% over the previous two years, and that global employment in clean energy sectors, 35 million, had exceeded that in fossil

dividends, together with a degree of decoupling of economic growth from growth in energy inputs. Electricity provides large efficiency gains in energy conversion and utilization compared with combustion, and renewables provide the option of less expensive energy than fossil fuels, derived from inexhaustible and decentralized sources (Jacobson, 2023; Walter *et al.*, 2024a,b).[65] Many have postulated that artificial intelligence also has the potential to spur significant productivity gains, as a possible catalyst for a fourth industrial revolution; others are considerably less sanguine about its promise and about its sustainability attributes, given its extremely high energy and water demands.[66]

Conclusions

Environmental damage is eroding global economic prosperity. It has been slowing productivity growth for decades and may already have halted or even reversed it.

Natural capital is the foundational asset underpinning the global economy. Its absence from economic frameworks has obscured the real costs of its depletion, generated incentives for unsustainable overexploitation of the natural environment, and artificially inflated conventional measures of productive capacity. The consequence is that we have collectively been running a natural capital deficit for decades that has diminished the total stock of productive capital.

As natural capital stocks 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. 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.

A necessary 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. Further, a key element of any productivity strategy should be investing in the preservation of natural capital and the reversal of its long-term decline.

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fuel industries (32 million) since 2021 (L. Cozzi et al., 2024). In electricity, renewable sources are expected to meet 95% of global demand growth between 2025 and 2027 (IEA, 2025).

[65] One prominent analyst has calculated that a transition to 100% renewable electricity and heat would reduce global end-use energy demand by 56% by 2050, due to efficiency gains and the elimination of energy consumed by fossil fuel and uranium production (Jacobson, 2023). A major caveat is, however, the Jevons Paradox, i.e. the observation that improvements in productive efficiency tend to result in increased rates of consumption.

[66] AI and associated data centres have become major drivers of rising demand for electricity, with an AI ChatGPT request using ten times as much power as a typical Google search (IEA, 2024). The IEA estimates that global electricity demand from data centres will more than double by 2030 (IEA, 2025). In the US, which accounts for the largest share of this increase, data centres are expected to account for nearly half of electricity demand growth through 2030. Water use by data centres is also rising steeply, with double-digit increases for Google and Microsoft in recent years, and a near doubling projected in the US between 2023 and 2028 (Shehabi et al., 2024).

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