Editors' Overview

The 47th issue of the *International Productivity Monitor* features two symposia: one on productivity and industrial policy, and the other on productivity and climate change. Each symposium includes three articles.

Recently, OECD countries have renewed their focus on industrial policies to address political, economic, and societal challenges. Historically, these policies involved the state selecting or protecting certain firms or sectors. Modern approaches now aim to address information and coordination failures. While industrial policies have been measured by their support for employment and strategic industries, productivity has often been overlooked.

The symposium on industrial policy and productivity explores the impact of industrial policy on productivity and economic performance. The first article by **Catherine Mann** from the Bank of England, the University of Manchester, and the University of Brandeis, argues that while global integration has historically driven productivity gains, rising geopolitical tensions and domestic economic concerns have led to increased use of industrial policies. These policies aim to address externalities and support key industries but often fail to match the effectiveness of global integration. She concludes that a combination of global engagement and well-targeted industrial policies is essential for reviving productivity growth and addressing inequalities amongst firms.

The second article by **Diane Coyle** and **Ayantola Alayande**, both from Cambridge University, examine the UK's industrial policy interventions in life sciences and pharmaceuticals, financial services, and the creative industries. Despite a historical aversion to active industrial policy, the UK has implemented sectoral policies "by accident." The authors are most positive about life sciences and pharmaceuticals, where stable policies have supported innovation and investment. In financial services, despite regulatory instability, infrastructure investments and innovation support have maintained the UK's status as an international financial center. For creative industries, success has often come despite government policies. The authors argue that intentional, strategic industrial policies could improve productivity through better coordination, reduced investment risk, and enhanced spillovers.

The final article in the symposium by **Tim Sargent** from the MacDonald Laurier Institute examines the effects of industrial policy on four Canadian sectors: steel mills, aluminum smelting, auto assembly, and aerospace. The study finds that aluminum smelting and auto assembly outperformed in terms of productivity growth, while the other two sectors showed disappointing results. The analysis suggests that industrial policy can support high-productivity industries and prevent their decline, but its overall impact on productivity growth is inconclusive. The article highlights the need for careful consideration of industrial policy's role in economic performance.

This symposium underscores the complex role of industrial policy in shaping better economic outcomes. While strategic, well-coordinated policies can enhance productivity and address inequalities, the effectiveness varies across sectors and regions. The findings highlight the need for tailored, evidence-based approaches to maximize the benefits of industrial policy.

Many consider climate change the existential issue of our age, with many ramifications for the economy and society. One issue related to climate change that has received limited attention is the implications for productivity performance. To shed light on this important relationship, the second symposium in this issue features three articles that explore various aspects of the climate change-productivity nexus.

In the first article in the symposium, **Dirk Pilat** from The Productivity Institute and the Valencia Institute for Economic Research provides a comprehensive exploration of the link between productivity and climate change. He finds that mainstream studies have significantly underestimated the damaging aspects of climate change for both growth and productivity, while overestimating the long-term costs of policies to address climate change. He recognizes that standard measures of productivity, like MFP, do not yet show a transition to a sustainable growth path and that the current pace of decoupling between CO2 emissions and GDP growth is far below what is needed to reach net zero. He concludes that the challenge for policy is how to design climate change policies to attain net zero while at the same time supporting productivity growth and living standards.

Standard multifactor productivity (MFP) measures often overlook environmental changes and climate change costs. **Carl Obst** from the Institute for the Development of Environmental-Economic Accounting addresses this by using ecosystem accounting to integrate the environment into MFP. He reviews frameworks for environmentally adjusted MFP estimates, focusing on three entry points: subtracting bad outputs from GDP, including natural capital inputs in production functions, and treating environmental expenditures as additional output. Obst develops an ecosystem MFP model, illustrating its application with an apple farmer. He identifies two main challenges: understanding and measuring the relationship between ecosystem physical flows and outputs, and estimating the cost shares relevant for ecosystem inputs.

The world has experienced a secular decline in productivity growth in recent years. At the same time, measures of natural capital produced by both the United Nations Environment Program (UNEP) and the World Bank show an absolute fall in natural capital, which includes ecosystem services affected by climate change. In the third article in the symposium, **Christina Caron** makes a case that the depletion of natural capital has directly contributed to the slowdown in productivity growth. In a comprehensive review of the literature, she provides many examples of how changes to natural capital, including damage to ecosystems from climate change, have negatively affected productivity. She concludes that natural capital has gone from a productivity accelerator to a productivity dampener, with climate change a key part of this story.

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Could Domestic Industrial Policies, Even With Global Fragmentation, Revive Productivity?

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Abstract

Many policymakers are using industrial policies more actively, while also pursuing policies tending to fragment global markets. Can this combination revive productivity growth? This essay starts with noting that an average productivity measure used to assess macroeconomic performance often masks important distributions of productivity outcomes, which matter economically, socially, and politically. It then reviews the frameworks that rationalize industrial policies and which derive the outcomes of global engagement. It then considers current empirical assessments of the effectiveness of industrial policies and current modeling work on the consequences of global fragmentation. It presents an overview of two new databases on detailed industrial policies as being deployed by policymakers. With regard to the question posed in the title, the answer is most surely 'no'. First because the deployed industrial policies rarely match the framework rationalizations. Second because the majority of those policies further fragment global markets. Therefore, globalization gains are being foregone while industrial policies are being mistargeted. That combination is not likely to revive productivity growth nor improve productivity distributions.

These days, policymakers face three developments: First, the trend toward deeper global engagement has been undermined by widening inequalities seen to be caused by global factors, by weakening of the multilateral rules of global institutions such as the IMF and WTO, and by rising geopolitical tensions and associated prioritization of domestic economic and national security concerns.

Second, an upswing in the deployment of domestic industrial policies, which purport to address a variety of externalities including domestic concerns regarding com-

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petitiveness of key industries, agglomeration and skill losses concentrated by region, incompleteness in financial markets with respect to firm size and type of investment, and a failure to price-in supply-chain shocks on externalities from global public goods such as climate change.

Third, the slowdown in productivity growth and the widening distribution between productivity leaders and laggards, whether firm or regions, which weakens the capacity of a countries' policymakers to improve the well-being of individuals, their communities, and their children.

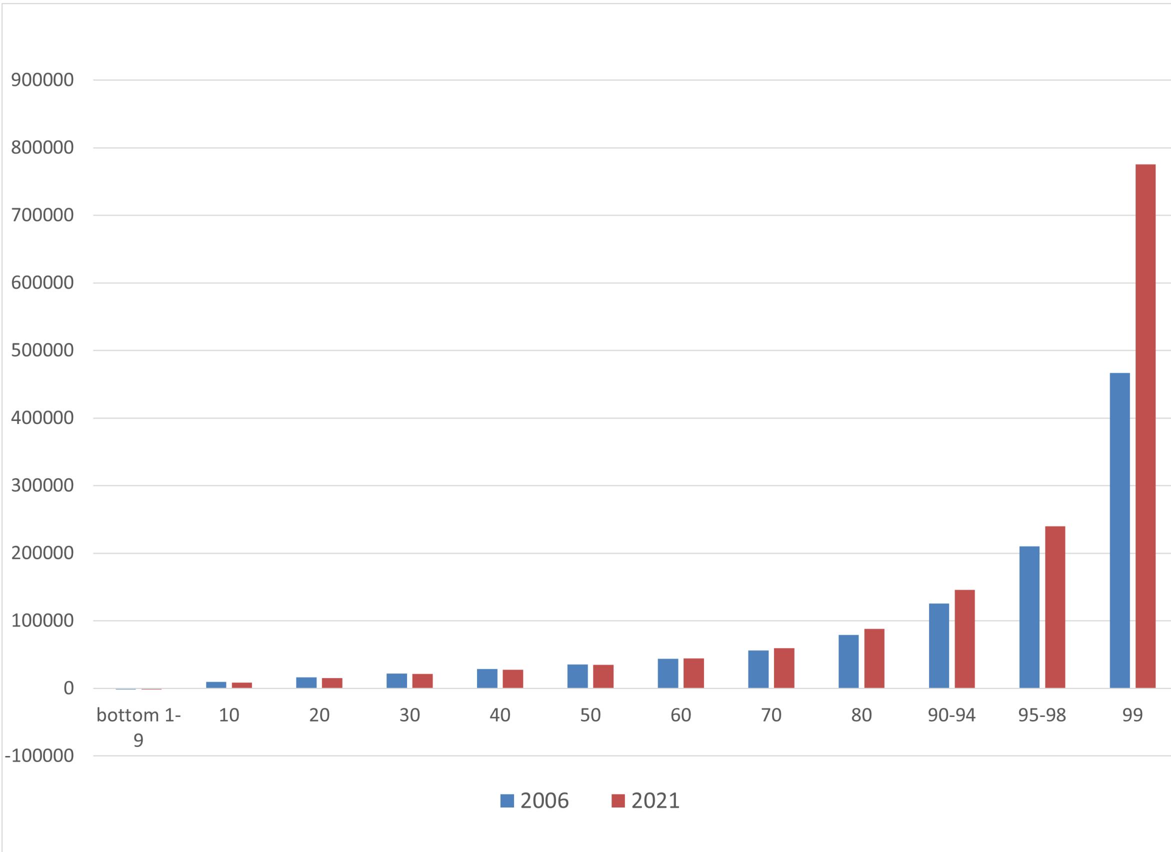
How do the first two developments intersect with the third? The policymakers' objective, to enhance productivity prospects, is key to increasing living standards. But it is clear that macroeconomic – that is, average – productivity growth is not the only concern. The distribution of productivity growth, across firms, regions, and intergenerational cohorts matters too, as these can feed back into the future trajectory of both overall productivity and its distribution. This nexus of productivity and inequalities, and research related to it, was outlined and reviewed in depth by OECD (2018) and Cho, *et al.*, (2024).

Where do industrial policy and global fragmentation fit into these productivity objectives? Should industrial policies focus mostly on ameliorating negative distributional consequences of global integration even as globalization drives further productivity gains? Or, should they bolster domestic outcomes in part by dampening global integration and its negatives? The first policy design – industrial policy to ameliorate globalization issues – suggests that domestic industrial policies could complement policies of global integration to revive overall productivity growth. It could do this by promoting adjustment strategies and by addressing externalities which together would help diffuse gains from global integration more evenly throughout the economy. The second policy design – domestic industrial policy combined with geoeconomic fragmentation — would appear to forego some gains from global integration and presume that domestic industrial policy can be sufficiently robust to generate productivity gains through domestic-based channels.

The answer to which pair of policies has the greatest potential to revive productivity growth may depend on how we think about and what research might reveal regarding the mean or aggregate productivity outcome versus the variation or distribution of productivity outcomes. It is common to use aggregate or economy-wide outcomes to judge policy, since this aggregate is relevant for macroeconomic assessment of productivity growth. But, the variation in firm (or regional or intergenerational) outcomes around the average clearly also is relevant.

Chart 1 shows the cumulative distribution of labour productivity in constant GBP for deciles (and some smaller percentiles) over time for the UK. Real labour productivity has been flat for near a quarter century for the lower half of the distribution. These workers are in firms often classified as 'laggards'. On the other hand, the real productivity gains enjoyed in firms at the productivity 'frontier' of the 90th and above percentiles is significant; dramatic for the 99th percentile at the top of the distribution. There are myriad inequal-

Chart 1: Average Labour Productivity Outcomes by Decile and Top Percentile in the United Kingdom, 2006 and 2021 (constant 2019 GBP)



Source: Annual Business Survey (ABS), Annual Business Inquiry (ABI) – Office for National Statistics (ONS).

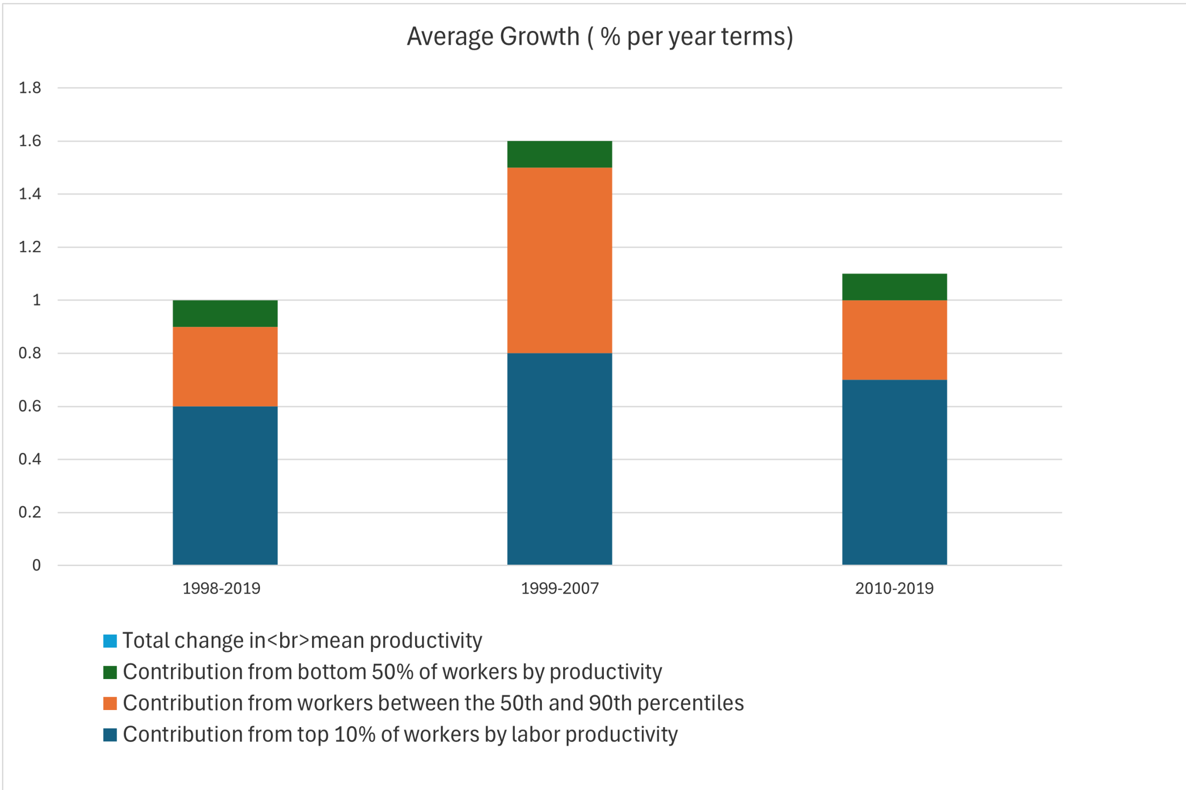
ities and both policy and political salience associated with this wide and widening distribution of productivity outcomes.

Chart 2 puts these data into perspective on the contribution of the various deciles of the level of productivity into contributions to productivity growth over various time periods. The observation from this presentation versus the previous one reveals that the slowing in productivity growth in the UK is predominantly at the core of the distribution (although the top decile has also slowed). There is a narrowing of the deciles in terms of contribution to productivity growth, but not in a good way.

Imagine a hypothetical alternative whereby the bottom half of the distribution become just somewhat more productive. Overall productivity growth would improve and the distribution of productivity outcomes would narrow, at least a bit. Can this improvement at the bottom be achieved along with a resumption of productivity in the middle and even as the frontier firms continue to pull away? The distribution and how productivity is achieved across the distribution matters for a number of reasons.

First, knowing the average but not the distribution is a poor representation of the productivity landscape of the economy. The average masks the policymaker challenge of how to increase productivity for the economy by addressing productivity

Chart 2: Contribution by Different Deciles to UK Labour Productivity Growth, Selected Periods



Note: Percentages may not sum up due to rounding.
Source: Office of National Statistics
https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/firmlevellabourproductivitymeasuresfromtheannualbusinesssurveygreatbritain/1998to2019

disparities that are important in both the present state and future trajectory of the economy. Second, wide productivity disparity might be related to lower economic resilience: An economy that depends on productivity performance of the leaders but with a large fraction of the economy with much lower productivity outcomes could be fragile in the face of shocks or global competition or other factors that disproportionately hit the relatively few productivity leaders.

The process of collecting data, applying measurement and conducting research is to provide guidance to policymakers. Given the three developments that prompted this essay, it tries to answer the question posed in the title by considering: What do we know about how global fragmentation and industrial policies might affect the mean and distribution of productivity outcomes. What are the objectives of policymakers and what policies are they apparently deploying to meet them. Will these revive productivity growth?

The first section of the article presents some fundamentals of the globalization and industrial policy frameworks, including the channels through with they purport to support productivity growth. An important focus is the extent to which these frameworks consider average or overall outcomes versus distribution of outcomes and potential vulnerabilities. Section 2 takes a look at the current discourse on these topics, that is, what recent research has to say about what might be given up with the trend toward global fragmentation versus what might be gained from industrial policies. Section 3 gives an overview of two new datasets of industrial polices as deployed. This section focuses on (1) whether there is a good match between the objectives of industrial policy (as outlined in the framework section) and the policies and their targets as actually deployed; and (2) how intertwined industrial policies and globalization policies apparently are and whether this is complementary to raising productivity growth or may be working against that goal. Section 4 offers some final observations

Global Integration, Industrial Policies, and Productivity Growth

The Fundamentals of Productivity Growth

Where does productivity growth come from? Transformation, total factor productivity, is central to productivity growth. Transformation, in products, processes, and workplace practices, when we consider the firm lens of analysis. As firms transform, so do regions and people who live and work there – successfully or not. Transformation needs a technological foundation of innovation; domestic and global competition to promote investment, learning, and innovation; and people skills to innovate, complement capital, and prosper in the overall transformation process. A recent report from The Productivity Institute (van Ark, de Vries and Pilat, 2024) puts it this way:

"The policy analysis identifies four categories of pro-productivity policies:

- **The accumulation of the factors of production** (e.g. policies focused on stimulating investment or strengthen education and skills)
- **Markets and resource allocation** (e.g. policies focused on improving the functioning of product and labour markets)
- **Technological and structural change** (e.g. policies focused on strengthening innovation)
- **Internationalization** (e.g. policies to enhance openness to trade or foreign direct investment)"

Stumbling blocks to these transformations will inhibit productivity growth.

When measuring productivity growth, it has been most common to use national aggregates, since it is this national aggregate that feeds into the overall capacity of an economy to deliver higher living standards. However, as noted earlier, as more granular data have come into research, it is increasingly relevant to evaluate productivity growth beyond the aggregate specifically to include firm and regional variation. For the UK, variation around aggregate measures of productivity growth along these two dimensions is substantial and has been increasing for some time yielding dismal aggregate productivity performance (van Ark and O'Mahoney, 2023). A look under the bonnet reveals that there has been a slowdown in productivity growth at the frontier (Coyle and Mei, 2022) as well as no catch-up of the lower half of the distribution of workers in firms (ONS, 2022), yielding a widening distribution of productivity outcomes. The slowdown in average productivity growth challenges policymakers in many countries, not just the UK, even as the specifics of the underlying productivity distribution and causes thereof varies across countries.

Given this firm, worker, and regional variation, an important question when thinking about pro-productivity policies is whether to focus on improving productivity of the leading firms, workers, and regions or whether improving outcomes along the wider set of laggards is better economically (and perhaps politically too). Do policies differ for leaders vs laggards? They probably do. For leaders, the policies might focus on pushing out the knowledge frontier, and these policies might involve domestic R&D, but also deepening global market opportunities and disciplines, with technology learning and upgrading, and more market competition. For laggards, the policies might focus on strategies to encourage agglomeration and diffusion, such as infrastructure and housing, skills development, and first-loss financing for riskier firms, with more specifics on policies to be discussed later. The empirical work discussed below present some of what we know about these strategies.

Global Integration and the Distribution of Productivity Growth: the Framework

How does global integration support the sources of productivity growth, but also affect the variation in productivity outcomes and possible vulnerabilities to shocks? Do all these 'run in reverse' with the slowing of the pace of global integration?

Sources of productivity growth from global integration, and the transformation that is assumed to take place to obtain those gains, has a very long history, both theoretical and empirical. Ricardo, Stolper-Samuelson, Intra-Industry Trade, and Schumpeterian theories all reveal sources of overall gains through the mechanisms of consumers and firms responding to prices, resource availability, competition, and market opportunities that generate those gains.

Changes in relative prices and differences in resource endowments, technologies, and tastes all incentivize consumers and therefore firms into the transformations of product and place that generate gains. Larger markets support economies of scale. More varieties through intra-industry trade enhance consumer well-being and availability of business inputs. Imports and/or production re-location increase efficiencies, reduce costs, enhance knowledge of 'close to consumer' preferences, and allow access to resources not available at home. Technology transfer, managerial development, and financial flows are all enhanced with global integration.

Suppose all firms and regions could transform in the face of the signals, incentives, and opportunities associated with global integration. We could trace out a global integration productivity frontier for an economy.

However, just as there is vast empirical evidence on these gains from global engagement, the facts are that not all firms, workers, and regions can transform so rapidly, leading to disparities in outcomes (Rodrick, 2024) manifested in the focus in this essay on both the productivity average as well as its distribution. As some firms access global markets to reap the benefits, including as measured by productivity growth, other firms and/or some regions, and the people there, may be left behind. Leading firms in pursuit of globalization and productivity gains for themselves, can leave agglomeration holes, income inequalities, and weakened knowledge diffusion, all of which negatively affect the productivity dynamic of firms in and of a region, and the people and communities there.

To the extent that some firms and regions struggle to transform then the overall potential productivity gain from global integration is not being achieved. The wider is the distribution, the less representative is the macroeconomic metric of average productivity growth and the further inside the possible productivity frontier associated with global integration the economy might lie.

In addition, global integration accentuated by technology has created complex supply networks, which is another lens on how the mean and distribution of productivity outcomes might matter. There is increasing appreciation that domestic and global value-chain specialization, which increases firm-level productivity, may not fully price infrequent shocks such as from climate, pandemics, or geopolitical stresses. Even if these tail shocks are becoming more frequent, their costs remain uncertain and hard for firms to value. However, if shocks were accounted for, firm costs probably would be higher and measured productivity growth likely lower. Any individual firm may not have the incentive to incorporate the cost of tail shocks, particularly if competitors do not. What policies might internalize this externality, and are there productivity consequences?

National policies toward supply chain restructuring could be viewed as a coordinating device to address the externality that comes from inconsistent firm approaches to incorporating tail risks. But, this national perspective and prescriptive approach runs the risk of global tit-for-tat backlash and a shrinking of product market opportunities for all firms. Such global fragmentation could reduce measured productivity growth, which raises the stakes for industrial policy to offset. Without commenting on the price of de-risking or of national security, it is more difficult to achieve those objectives when operating in a low productivity environment.

Industrial Policies and the Distribution of Productivity Growth: the Framework

Industrial policy has a somewhat eclectic theoretical heritage, but a key theme is that industrial policies should address externalities where private returns and societal benefits diverge, either at a point in time or dynamically over time, either within a country or with global objectives. The definition of societal benefits can be quite broad such that a wide array of objectives and microeconomic policies could fall within scope. Juhász, Lane, and Rodrik (2023) define industrial policy as "government policies that explicitly target the transformation of the structure of economic activity in pursuit of some public goal." Productivity growth might be a goal, but there are many others too. And, industrial policies need not have just a domestic focus: Externalities associated with global societal objectives, for example addressing mitigation and adaptation associated with climate change or biodiversity loss, also could be in-scope for industrial policy.

Getting more detailed and policy operational, Warwick (2013) sets out a framework that moves from product-market interventions, such as to develop infant-industry competitiveness; to factor-market interventions, such as the market's failure to finance optimal R&D; to systems-intervention issues, ranging from network externalities to governance. Chriscuolo, Gonne, Kitazawa, Lalanne (2022) take another stab at an encompassing framework with an eye toward mapping objectives to policies to instruments, with a clearer focus on productivity growth as the goal. Industrial policies can be mission-oriented (such as the 1960's moon-shot with productivity spillovers), place-based (to enhance transformation and narrow the productivity distribution), and/or sectoral and technology focused (including national security, strategic, and winner-take-all concerns).

Mazzucato's (2024) broadens the challenge: "Modern industrial policy should shape markets, not just fix their failures." In this view, industrial policy should take a pro-active stance toward economy-wide structural change to raise overall productivity growth in an inclusive way. Such an industrial policy could focus on a catalytic role for the public sector to boost innovation by domestic firms and within regions to enhance productivity growth overall (Kattel and Mazzucato, 2018). A specific example of this might be the success of the 'Asian Tigers' as government interventions pushed domestic firms to move away from heavy industries to manufacturing (Chriscuolo, Gonne, Kitazawa, Lalanne, 2022: Box 1).

Because governance plays a central role in industrial policy, considering the effectiveness of the state and the relationship between governance and productivity is receiving renewed attention. See the UK case in Pabst and Westwood (2021). Following in the steps of the 2013 assessment by Crafts and Hughes (2013), Juhasz and Lane (2024) pursue a more general discussion of the political economy of industrial policy. In terms of political economy and accountability, a relevant question is whether bad policies matter for political outcomes: the evidence is not clear. Voters may turf-out the incumbents, but the incoming administration does not appear to achieve better outcomes, at least as measured by employment. (Marinova, 2024). And, voters may turf-out the incumbents based more on misinformation than on economics anyway. (Hellwig and Marinova, 2015).

Global Integration and Industrial Policies: Complementary or Separate?

Given the presence of a left-behind tail of firms and regions struggling to transform, the implication is that the economy is operating inside some possible productivity frontier. The globalization theories indicate that the gains are large enough to be redistributed to make everyone better off. But the globally-focused theories do not say whether or through what policies the gains accruing to the leading firms can either be distributed to, or effectively received to pull up the laggards. And the empirical facts evidence that these redistributions either have not taken place or have not been successful at meeting the transformation challenge (Juhasz, Lane, Rodrick, 2023).

Given this externality, can industrial policy be deployed to accelerate the transformation of left-behind firms and regions so that the maximum productivity gains from globalization can be achieved? This thinking could make policies of global engagement and domestic industrial policy complementary; and thinking in these terms could put the process of global integration and associated productivity growth back on track. Both industrial policy and global integration are needed to reach the highest average productivity. But in this view global integration is the primary driver of productivity growth, with industrial policies designed to ameliorate the distribution problem, resulting in a closing of the gap between the actual and possible productivity frontier.

In contrast, advocates of domestic-focused pro-active industrial policies argue that these policies will better achieve the goal of productivity growth, or at least of society without the distribution of leaders and laggards characterized by global integration. The incentives, disciplines, and rising distributional consequences of deepening global integration should not be the default to be remedied.

With pro-active policies in place, presumably firms and regions are less likely to fall behind the leaders – the tide does lift all boats. There should be less of a distribution in productivity outcomes and that contributes to a smaller gap between the potential productivity frontier and the actual one. However, does the tightening of the distribution of productivity outcomes come at the expense of higher productivity growth as measured by the mean? The bar is high, since domestic industrial policy would need to be sufficiently robust at generating productivity gains at the frontier as well as across the distribution of firms and regions to match the productivity growth associated with deeper global integration.

The complementarity of industrial policy and global engagement would appear to be the optimal strategy to raise average productivity growth two ways—at the frontier and among the laggards. The question still remains, on balance should policymakers focus on pro-active industrial policies while still deepening global engagement. Or should the trend toward global fragmentation be accepted, or even welcomed on account of the distributional issues? Mann (2019) concludes, "if globalization has peaked, this portends fewer resources to address inequalities regardless of their proximate cause. From this perspective, the problem is not too much globalization, but too little. To address the adjustment and distributional challenges, we need both to reinvigorate globalization and to deploy domestic policies to ensure that the gains are widely shared."

Empirical Evaluation of Global Fragmentation and Industrial Policy

With industrial policy being deployed more aggressively and more targeted and global fragmentation becoming more entrenched and policies more explicit, empirical research is starting to shed light on implications for global output and its distribution, albeit with limited attention specifically to productivity growth. This research allows a first stab at the question of whether gains from deploying domestic industrial policy could offset losses from global fragmentation. Although early days and difficult to compare scenarios across estimation methodologies, the results suggest that the losses from global fragmentation are macroeconomically material and the gains from deploying industrial policy more notable only for certain sectors.

A comprehensive report from the IMF (Aiyar, Ilyina, and others, 2023) details the state of globalization and then addresses various pressures for fragmentation. A recent CEPR volume (Aiyar, Presbitero and Ruta, 2023) assesses the costs of global fragmentation from a number of perspectives, including friend-shoring, commodities, innovation spillovers, FDI fragmentation, and uncertainty and bank lending. A symposium on industrial policies in the Fall 2024 issue of the *Journal of Economic Perspectives* offers views on picking export winners (Reed, 2024), lessons from shipbuilding (Barwick, Kalouptsidi and Bin Zahur, 2024) and semiconductors (Bown and Wang, 2024), political economy (Juhasz and Lane, 2024) and a reprise on Alexander Hamilton's Report on Manufactures (Sylla, 2024).

Global Fragmentation: Empirical Assessment

A number of recent papers use a variety of empirical models to run scenarios of different types of global fragmentation to quantify the losses to GDP for different regions, with some attention to productivity growth. There is much more to analyze.

Hakobyan, Meleshchuk, and Zymek (2023) takes the global perspective and assesses losses from global fragmentation through the lens of greater sensitivity of trade to geopolitics. The authors use a many-country many-sector gravity model and parameterize distance to include geopolitical alignment. Geopolitical trade sensitivity appears most relevant for foods, transport equipment, and other manufacturing. Geoeconomic fragmentation increases distance, which reduces trade and GDP. Emerging markets and developing countries are worst off. Joining nonaligned blocs using regional trade agreements can offset some of the overall losses, but incompletely so. As is well known, regional trade agreements are less productivity enhancing than global engagement on account of 'spaghetti bowl' costs associated with rules-of-origin.

Baba *et al.* (2023) focuses on the EU and the channels of trade, finance, and intellectual property flows. In the case of a strict form of global fragmented, with four autarkic blocs without cross-bloc trade in goods, knowledge and FDI (United States, EU, China, Rest of the World), GDP losses are huge – some 5 to 10 per cent. If the EU retained global relationships in the face of US-China decoupling, the losses are dramatically smaller, only 0.25 to 0.5 per cent of GDP. Maintaining geoeconomic neutrality is difficult, especially given the intertwining of technological inputs and the extra-territorial reach of technology sanctions. In thinking about the relationship between global fragmentation and industrial policies, if industrial policies in the EU were defined to include deepening the EU's single market, EU GDP would increase even in the face of other parts of the world fragmenting. This deepening of the single market enhances the power of industrial policy because spillovers from one country become positive spillbacks to another.

Cerdeiro, Kamali, Kothari and Muir (2024) address supply-chain reconfiguration (re-shoring and friend-shoring) with China and OECD members in focus. If the structure of global integration returned to its year-2000 relationships –foregoing a quarter century of global integration– global GDP would be 4.5 per cent lower. The authors also consider consequences of supply chain reconfiguration just in certain strategic products by measuring the change in the quality of inputs. For example, if supply chain rules of re-shoring and friend-shoring were applied to environmental goods, quality could decline by some 5 per cent for the OECD aggregate, with knock-on effects to lower productivity growth.

Financial fragmentation is also a consequence of overall global fragmentation (IMF, 2023). Financial fragmentation brought on by geopolitical tensions can affect financial stability through the volume and allocation of capital. The divergence in voting behavior of the United States and China at the United Nations since 2016 is one measure of geopolitical tensions. A one-standard deviation increase in this measure could reduce cross-border portfolio and bank allocation by about 15 per cent, probably reducing the availability of financial capital needed for productivity enhancing investment.

Industrial Policies: Empirical Assessment

The empirical work on economic gains from pursuing industrial policy is more mixed, in part because the objectives and tools of industrial policy are somewhat diffuse. This means that comparing industrial policy and global fragmentation side-by-side to assess productivity growth by sector, region, firm size, or even macro average will be difficult. However, this research using firm-level data and detailed policies should help to prioritize industrial policy strategies, and will therefore be foundational to the assessment of whether the policies that are currently being deployed (as discussed in Section 3) match those identified by the research as best practice.

One approach to assessing industrial policy focuses wholistically on the industrial policy implementation and environment, recognizing that industrial policies have been part of the landscape for decades, but assessing their effectiveness has been challenged by definition of success and institutional context. This new work is case-study focused, and therefore quite different in scope and method from either macro models or analysis using large firm-level datasets. The empirical test for this work is whether industrial policy did focus resources in the desired areas, not more narrowly on, say, whether there were productivity gains. Therefore, it is difficult to map these successes against the quantitative experiments of the losses from global fragmentation. (Juhász, Lane, and Rodrik, 2023)

A second approach, using very detailed data on industrial policies and firms, comes from the OECD researchers, Criscuolo, Gonne, Kitazawa, and LaLanne (2022). They develop a taxonomy for industrial policy that distinguishes between industrial policy that focuses on supply enhancing productivity versus demand generating productivity. This initial findings show that:

- R&D tax credits and subsidies can stimulate R&D and innovation, so long as policies to enhance diffusion are in place as well. This finding is consistent with the discussion above whereby just pushing out the frontier through supporting higher productivity growth for leading firms widens the spread of productivity growth outcomes leaving the average, or macro, measure of productivity growth less representative of the economy overall, and more fragile to stumbles by the leading firms.
- Positive productivity outcomes associated with grants and subsidies is not clear, but to the extent that these policies do enhance productivity, it is by targeting to young and small firms, not large or multinational firms. In part, the targeting to the smaller and younger firms acts as a signal to financial investors, reducing information asymmetries, and contributing to needed financial capital for productivity enhancing investments.

- Maximum effectiveness of industrial policy comes when competition and trade policies support transformation and allow the most productive firms to grow. This points to the complementarity of global integration and domestic industrial policies, and implies that global fragmentation would be a headwind for industrial policies.

As background to the complementarity of global engagement and industrial policy, OECD researchers Andrews, Criscuolo, and Gal (2015) consider relationships between domestic firms and foreign firms. There are firms comprising a global productivity frontier, firms that comprise a national productivity frontier and then laggards in the national context. There are two types of catch-up – national frontier firms to the global frontier and national laggards to the national frontier. Deepening global engagement pushes out the national frontier to the global frontier. Catch-up among national laggards through technology diffusion is enhanced when the national frontier firms adapt global frontier technologies to "country-specific circumstances". This adaptation is enabled by domestic policies that ensure reallocation of resources to the adjusting firms although various approaches to R&D policies are also relevant. Empirical assessment of potential productivity gains are highly country and policy specific.

Further analysis, again using the detailed cross-country policy data at the OECD, by Berlingieri *et al* (2020) on the laggards details the type of industrial policies that could help raise their productivity. Laggards are smaller and younger, and over time, if the survive, they catch-up faster to the frontier the further away they start from it. Therefore, at least some of the current laggards will be the productivity drivers of the future. However this pace of catch-up has slowed, which is an important ingredient in the overall slowing of productivity growth. Better digital skills, loosened financial constraints, and government support of R&D appear to be relevant policies to spur faster catch-up. Research finds that increasing the productivity of laggards to the level of the median firm (i.e., by about 60 per cent) could, on average, increase aggregate productivity by roughly 6 per cent. Results vary by country

Criscuolo, Martin, Overman, and Van Reenen (2019) focus on subsidies for investment and productivity growth using firm-level data. The authors find that a 10-percentage point increase in the investment subsidy stimulates a 10 per cent increase in manufacturing employment, only on account of small firms responding. Large companies accept subsidies without increasing activity. There are positive effects on investment and employment for incumbent firms but not productivity.

Industrial policy for regions is the focus of Bolter and Robey (2020) and Graham, Gibbons, and Martin (2009). The first authors argue that achieving agglomeration economies is central to regional success. Policies might best support agglomeration include workforce skills and transportation linkages to create density, which then build on each other to further attract firms and boost agglomeration economies. Agglomeration gains include increased employment, wages, and productivity levels. The second set of authors estimate that, for UK cities, doubling a city size would increase productivity by 2.4 per cent for manufacturing and consumer services, 3.4 per cent for construction, and 8.3 per cent for business services.

NIPO and QuIS Datasets on Industrial Policies: Type, Target, and Cost

Section 1 outlined frameworks that suggested that global engagement raises the productivity bar, but can lead to a wider productivity distribution and then how industrial policies focused on market failures could raise both productivity mean and narrow the distribution. Section 2 presented research evidence on the potential GDP and productivity losses from global fragmentation and on the productivity outcome of various kinds of industrial policies.

Given these frameworks and associated empirical evaluations, the next question is: What type of industrial policy is actually being deployed and does this match with the market failures highlighted by the industrial policy frameworks and with what the empirical research indicate is the type of industrial policy most likely to raise average productivity growth?

There are two datasets that allow a preliminary assessment of how industrial policy is actually being targeted and deployed: The New Industrial Policy Observatory (NIPO), now available from the IMF, and the Quantifying Industrial Strategy (QuIS) from the OECD. The top-line conclusion from a look at what industrial policies are actually being deployed is:

- On climate, there is a good match between industrial policy to focus on the global public good of climate transition.
- On most every other objective, there is

a poorer match between what the externalities of the industrial policy framework indicates would be the best strategy by policy, sector, and firm size and what is actually being deployed.

- Rather than being complementary to global integration, the industrial policies that are actually deployed tend to undermine global integration.
- Industrial policies appear to favor incumbent firms in traditional industries rather than be targeted to innovative new firms.
- With regard to whether industrial policies target the laggard firms with lower productivity growth, the two datasets give somewhat different views.

According to NIPO, industrial policy as deployed appears to favor large incumbents. According to QuIS, SMEs do get some benefits, albeit varying by country.

A look at the New Industrial Policy Observatory (Evenett *et al.*, 2024) in more detail finds:

- Over the first 12 months of data collection, NIPO recorded over 2,500 IPs worldwide.
  - 71 per cent are trade distorting.
  - Corporate subsidies are the most common type of trade-distorting instrument.
  - In many cases, industrial policy support is deployed to firms already exporting, not infant industries or SMEs needing support to grow.
- China, European Union, and United States accounted for 48 per cent of the measures.
- In terms of motivation or targets (adding to more than 100 per cent of incidents because some policies are classified with more than one objective:)
  - Strategic competitiveness accounts for about 1/3 of measures.
  - Climate change accounts for 28 per cent.
  - Supply chain resilience for 15 per cent.
  - National security and geopolitical tensions combined account for 20 per cent.
- In terms of sectoral emphasis: military/civilian dual use products and advanced technology products, including low-carbon technology, semiconductors, and their upstream inputs such as critical minerals.

Noting the close association, as deployed, with industrial policy being trade distorting, Evenett *et al.* (2024) caution that "geoeconomic fragmentation could be self-reinforcing and hard to reverse. This is because larger research-intensive economies tend to have more domestic spillovers and, as such, greater incentives to implement industrial policies, which often entail preferential treatment for domestic industries."

The second data set evaluates not just the deployment of industrial policy but also the costs. The QuIS (Quantifying Industrial Strategies) database from the OECD gathers data on industrial policy expenditures at the policy instrument level categorized by instrument type and eligibility criteria. (Criscuolo *et. al*, 2022). This initial analysis of 9 OECD countries finds that the cost of deploying industrial policies is sizeable, with 1.5 per cent of GDP in grants and tax expenditures, and an additional

1.8 per cent of GDP through financial instruments (loans, loan guarantees, equity investments) much of which is focused on SMEs, including 1.1 per cent of GDP on export finance schemes. There is important heterogeneity across countries. For example: grants and tax expenditures range from 0.6 per cent of GDP in Ireland to 2.3 per cent in the United Kingdom. Financial instruments range from 0.4 per cent of GDP in Ireland and the United Kingdom to 5.4 per cent in Canada, where the larger expenditure is mainly explained by a higher level of export finance.

In terms of strategic priorities, industrial strategies mainly rely on sectoral instruments, representing on average 29 per cent of grants and tax expenditures; green instruments are increasingly important and account for 15 per cent. There is also a considerable degree of heterogeneity in terms of strategic priorities.

- 34 per cent of grants and tax expenditures are green in Denmark versus less than 1 per cent in Ireland;
- 35 per cent is related to jobs and skills in France versus less than 1 per cent in Israel.
- 'SMEs and young firms' represent 30 per cent of grants and tax expenditures in the Netherlands, compared with 12 per cent on average across the country sample.

Concluding Observations

This essay offers a view of productivity growth which argues that both mean or aggregate macroeconomic as well as the distribution across firms and regions are important for an overall assessment of the productivity landscape for an economy. This distinction matters for three reasons. First, policies to promote absorption or diffusion from the frontier (domestic or global) likely differ from policies to push out the frontier. Second, the wider is the distribution the less representative is the average or macroeconomic productivity measures and the greater is the absorption and diffusion challenge. Third, the wider is the distribution the more fragile is the macroeconomic average to possible slowing of productivity growth at the frontier firms.

The article then reviews frameworks that link global integration on the one hand, and industrial policy on the other hand to productivity growth. The links for global integration are well understood to achieve an increase in average productivity growth, but there is more skepticism about distributional outcomes. The links for industrial policy and productivity growth are more diffuse and varied, but importantly relate to externalities or market failures that may hamper the achieving of possible productivity gains.

The essay considers empirical evidence on losses from global fragmentation and potential gains from industrial policy. Methods vary too much for any side-by-side comparison. Neither address productivity growth per se but couch conclusions in more general terms of GDP growth. Nevertheless the losses from global fragmentation seem large and widespread whereas the gains from industrial policy seem to be smaller and more concentrated in targeted sectors.

Finally, the essay reviews two datasets on industrial policies to determine to what extent industrial policy, as it is actually deployed, matches the types of externalities and market failures that the industrial policy framework purports to have as objectives. The conclusion from NIPO appears to be that there is an alignment between industrial policy to target green investment and the externality of global public goods to meet the climate challenge. However, there is little overlap between what the framework analysis says should be deployed to improve domestic productivity outcomes and what is being deployed. In particular, rather than industrial policy being used to offset any globalization losses, three-quarters of industrial policies as deployed appear to be further trade distorting. The emphasis is on subsidies to incumbent firms in traditional sectors rather than support for left-behind firms or regions or support for innovative next generation productivity leaders. More critical, the research suggests that the types and targets of policy as deployed do not yield much productivity gain.

The QuIS database evaluates the cost of industrial policies to the fiscal purse, which is not insubstantial. To afford these policies, higher productivity growth is needed. Undermining global integration as a key foundation for productivity growth would appear to reduce the ability of a policymaker to pay for industrial policies.

To conclude: The answer to the question in the title is almost surely no. There is a true need to focus attention on raising the productivity growth of the lagging firms and regions. Empirical research using granular data on industrial policies shows which policies do work. However, data on the industrial policies as currently deployed imply that these do not appear to match well the market failures they purport to address, nor the policies that research finds most effective. Moreover, the policies being deployed are overwhelming distortive to global engagement. Therefore, globalization gains are being foregone while industrial policies are being mistargeted. That combination is not likely to revive productivity growth or improve productivity distribution.

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Productivity and Industrial Policy by Design: The UK Experience

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Abstract

The number of industrial policy interventions and the scale of the public expenditure involved is on the increase globally. The United Kingdom has a history of churn with respect to industrial policies, and has largely been averse to policy activism in this area since 1980. This article presents case studies of three UK sectors – life sciences and pharma, financial services and the creative industries – arguing that despite the anti-activism policy rhetoric for much of the past four decades these have experienced sectoral industrial policies 'by accident', involving classic policy tools used without a strategic framework. Policies affecting business decisions cannot avoid having an impact; acts of omission are policy choices, just as much as positive decisions. We argue that, although counterfactual outcomes are necessarily speculative, productivity outcomes would be better if policies impacting key sectors of the economy were developed by design, due to improved policy co-ordination, derisking of investment and more effective realization of spillovers.

After some five decades out of fashion, at least in terms of rhetoric, industrial policy is high on the agenda in many countries. The number of industrial policy interventions and the scale of the public expenditure involved is on the increase globally, and particularly in Organisation for Economic Co-operation and Development (OECD) economies (Criscuolo *et al.*, 2022; Juhász, Lane & Rodrik, 2023; Evenett *et al.*, 2024). There are several reasons for the re-emergence of a type of policy out of favour politically in the period since the introduction in economic policy of a market-first philosophy by Margaret Thatcher and Ronald Reagan of the 1980s.

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In addition to the imperative for macroeconomic stabilisation policies, the supply side shocks experienced since the 2008-9 financial crisis, including the 2020-21 pandemic and 2022 Russian invasion of Ukraine, revealed the existence of various supply chain bottlenecks in globalized production networks. Geopolitical tensions have underlined concerns about economic resilience (Aiyar *et al.*, 2023). Moreover, the global economy is in the midst of two structural technological transformations, namely the energy system transition to net zero and the new wave of AI and digital technologies. The market structures and patterns of comparative advantage established in the short to medium term as these two general purpose technologies advance and diffuse will shape countries' economic fortunes for decades to come.

The recent rise of industrial policies therefore signals governments' recognition – to varying degrees – that establishing a strategic framework for the supply side of the economy is timely. While this recognition has other motivations than improving productivity – such as national security and economic resilience – there are also hopes that reviving industrial policy by design can help tackle the slowdown in trend productivity growth.

There is of course a gap between rhetoric and reality. Governments have never stopped using some industrial policy tools even as they downplayed or critiqued the idea of actively shaping production activities (Crafts and Hughes, 2014). 'Horizontal' policy tools such as public spending on basic research, tax credits for research and development (R&D), export credit guarantees and infrastructure investment have always been part of the policy armoury. Some 'verticals' have long been explicitly supported, such as defence R&D and production, or basic industries such as steel, on national security or resilience grounds. And the pandemic brought a significant set of government interventions to produce, manufacture and distribute new vaccines rapidly and at scale, in some cases involving explicit setting aside of market economic principles, such as the invocation in the US of the Defense Production Act of 1950 (Bown, 2022).

The focus of this article is on UK industrial policies in recent decades that have not been characterized as such by policymakers. Specifically, we describe how successive UK governments have implemented 'accidental' industrial policies in three sector verticals, pharmaceuticals and life sciences, the creative industries and financial services. These sectors have been variously recognized as areas of UK economic strength in the intermittent explicit industrial policy initiatives introduced since Mrs Thatcher significantly downgraded the National Economic Development Office (NEDO) on attaining office (it was finally abolished by her successor, John Major, in 1992). These policies were introduced by the Labour Government in 2008-2010, the Coalition Government in 2012-2015 and, most explicitly, Theresa May's Conservative Government in 2017-2019 (HM Government, 2009; Department for Business, Innovation and Skills - BIS, 2012; HM Government, 2017).

However, they fell far short of an intentional, strategic approach to developing the UK economy's supply side strengths; rather, in each case there has been a succession of measures not informed by or located within a sustained national strategy. Moreover, a sectoral approach is still regarded with suspicion by some economists as a return to 1970s-style 'picking winners' or promoting 'national champions' et the expense of consumers (Posen, 2023; Owen 2024). The Labour Government elected in 2024 intends to implement a new industrial strategy.

We argue that a strategic industrial policy by design, rather than by happenstance, in three high value, export-rich sectors could have produced better productivity outcomes than the ad hoc interventions that actually occurred. One reason is that an intentional industrial policy framework can act as a device for joining up, or in other words co-ordinating, government interventions across different domains, such as infrastructure, skills, R&D and place-based policies. The lack of joining-up across government is widely recognized as a dysfunction of the UK economy, which increases the likelihood that there will be some unaddressed barriers to growth preventing other policies from having their potential impact (Coyle and Muhtar 2023a; Kremer 1993).

Better policy co-ordination increases the potential impact of government action on productivity, first by creating a consistent regulatory and tax environment and thereby helping derisk private investment; and second by elucidating trade-offs such as between consumer protection and innovation. A further mechanism for industrial policy to increase productivity is the improved potential it offers to realize spillovers such as those due to agglomeration or knowledge transfer. As a quantitative demonstration of counterfactual outcomes is not possible, we use three case studies to illustrate the impacts of implementing industrial policies by accident rather than design. Importantly, we include service sectors of the economy, which have often been overlooked in the industrial policy literature (Rodrik and Sabel 2022).

A Brief History of Formal UK Industrial Policies Since 1979

The Thatcher Government elected in May 1979 inherited the National Economic Development Office NEDO (or 'Neddy') as the main vehicle for determining industrial policies. Established in 1963, it formalized tripartite relations between the government, employers and unions, and operated through sectoral sub-committees known as 'little Neddies'. Mrs Thatcher promptly moved to replace its monthly meetings with quarterly ones, with senior government attendance only once a year. In a BBC interview on the occasion of NEDO's 25th anniversary in 1987, she said:

> "Yes things are different; we are much more market oriented, and what does that mean? It is not a great economic theory. What the market means is that the wage earner and the housewife go down to market, they decide what they want to buy and therefore they decide whose goods should be prosperous and successful (COI, 1987)"

In 1988, her Government also abolished the sectoral structure ("sponsorship divisions") of the Department of Trade and Industry (as it was then called), leading to a significant reduction in the civil service's engagement with industry and thus its knowledge and expertize, and also a reduced ability on the part of business to communicate with government (Greaves, 2008). In 1992 NEDO was abolished by Conservative Prime Minister John Major.

The Labour Governments in power from 1997-2010 were somewhat less allergic than the Conservatives to the potential role that the state might play in economic strategy; indeed, Chancellor Gordon Brown as a young radical Rector of Edinburgh University had called for a socialist society (Brown, 1975). New Labour in power also largely adhered to a market-first vision for the economy in terms of its political rhetoric. As Jones (2018) has noted:

> "The industrial policy of the Conservative governments between 1979 and 1997 was to not have an industrial policy. The New Labour government of 1997 broadly accepted this consensus, in particular resisting so-called vertical industrial policy—that is, specific measures in support of particular industrial sectors,".

The Labour Secretary of State for Business, Peter Mandelson nevertheless pushed for an industrial policy in 2009, as a means of enabling economic growth to recover after the financial crisis. The focus was indeed on 'horizontal' measures intended to enhance the UK's R&D, upskill the labour force, stimulate innovation in science and technology, and ensure a low-carbon transition (HM Government, 2009).

This nascent strategy was brought to a halt by the election of 2010, which brought to power a Conservative-Liberal Democrat coalition. In the coalition period, it was again the Business minister, now Vince Cable, who re-introduced an industrial policy in 2012. It included a focus on finance for investment and basic research, but also on packages of measures to support specific sectors: advanced manufacturing including life sciences, knowledge-intensive traded services including finance, and 'enabling' sectors such as energy and construction (Department for Business, Innovation and Skills (BIS), 2012). The 2012 paper discusses the risks of a sector-based approach but sets out a long list of reasons for nevertheless adopting it. This list includes the observation that, "Sectoral shifts reflect increasing sectoral specialization across all the advanced economies whereby a small number of sectors account for a relatively large share of GDP," (BIS, 2012:12). In other words, the argument it made was that the nation's economic fortunes are increasingly dependent on the performance of a relatively small number of sectors.

The final episode in this brief history is the Industrial Strategy of Greg Clark, Business minister in Theresa May's Conservative government. The 2017 document (HM Government, 2017) was framed around horizontal policy 'pillars' but also included sector 'deals', with an emphasis on technological innovation. These were: life sciences, construction, artificial intelligence and the automotive sector. The government also set up an Industrial Strategy Council consisting of business representatives and experts to advise it on policy. Yet again, a change of government overturned the policy, even though May's successor Boris Johnson was a member of the same party. His government promptly scrapped

Table 1: Sectoral Focus in Successive UK Governments' Industrial Strategies

New Labour 2008	Coalition 2012	May 2017	Johnson 2021	Labour 2024
Life Sciences /Pharmaceuticals	Advanced manufacturing (Aerospace, automotive, life sciences)	Life Sciences	Space	Life sciences
				Aerospace defence
Advanced manufacturing		Automotive		Advanced manufacturing
Professional Services/Finance	Knowledge-Intensive services (finance, information services, higher education)	Creative sector	-	Financial services Professional & Business services
				Creative industries
Net Zero (low-carbon vehicles)	Energy	-	Net zero/energy	Clean energy industries
Engineering Construction	Construction	Construction	-	-
Digital	-	AI	AI	Digital technology

the Strategy (and the Council), replacing it with a 'Plan for Growth' in 2021. The Labour Government elected in 2024 has announced a planned Industrial Strategy (UK Government 2024), signaling a sectoral focus, and has established an independent Industrial Strategy Council.

There has been some consistency over time in the sectoral strengths, or hoped-for strengths, identified by successive governments (Table 1). The Chancellor in the most recent Conservative Government, Jeremy Hunt, in a 2023 speech on economic growth prospects echoed some of the earlier policies in citing digital technology, green industries, life sciences, advanced manufacturing and the creative industries.[2] The 2024 Labour Government has pointed to similar priority sectors in its statements on industrial policy and "missions". However, below the level of identifying broad sectoral strengths, the policy environment has been characterized by significant policy churn and a lack of the co-ordination among government departments and other public bodies needed to implement an effective strategic supply-side framework (Coyle and Muhtar, 2023a, 2023b; House of Lords, 2024). The next section turns to three sectors identified by successive governments as UK economic strengths to describe their trajectories and the policy shifts affecting them over time: pharmaceuticals/life sciences, financial services and the creative sector.

The UK's Accidental Industrial Policies

In this section we describe how successive governments have, by accident rather than by design, operated what could be fairly characterized as sector-based industrial policies since 1990, despite the strong

2 https://www.gov.uk/government/news/chancellor-sets-out-long-term-vision-to-grow-the-economy

Figure 1:Taxonomy of Policy Instruments by Economic Welfare Rationale

Source: Coyle (2024)

emphasis on private business and markets in the rhetoric of economic policy. We adopt a broad definition of industrial policies as supply side interventions supporting a strategic policy goal such as economic growth or national security. This encompasses other definitions in the literature. For example, Juhász *et al.*, (2023:4) define industrial policy as,

> "Those government policies that explicitly target the transformation of the structure of economic activity in pursuit of some public goal,"

while Evenett *et al.*, (2024:6) go for,

> "Any targeted government intervention aimed at developing or supporting specific domestic firms, industries, or economic activities to achieve national economic or noneconomic (e.g., security, social, or environmental) objectives,"

These and other definitions all specify the intentionality and strategic character of industrial policies 'by design' (while recognizing that ad hoc or firm specific interventions are common), whereas we argue that policies adopted with a less well-specified strategic rationale are also industrial policies, but 'by accident'; many of those described in this section were introduced with a general notion of supporting an important sector of the economy, or a response to lobbying or the broader political economy environment, rather than a reasoned analysis of supply-side aims and what policy instruments might best service them. Acts of omission are still acts. What's more, the specific nature of the interventions has changed quite a lot over time in each case.

The examples we give here also demonstrate the use of a range of differing policy instruments. Figure 1 sets out a taxonomy of policies organized according to their economic welfare rationale. The mix of instruments used has been different across each of our three examples, as described below.

Table 2 presents some summary descriptive statistics for the three sectors, each of which accounts for a meaningful share of GDP. Chart 1 shows labour productivity (Gross Value Added, GVA per hour worked) for each sector and the total econ-

Table 2: Sectoral Descriptive Statistics (2022 or latest available data)

Sector	GVA	Share of GDP, Per cent	Number Employed	Average Earnings	Net Trade Balance
Life sciences/pharma	£43.3bn	1.2	304,190	£40,000	£625m
Financial services	£171.4bn	7.5	1,148,000	£48,197	£59.9bn
Creative Sector	£148.7bn	6.5	2,300,000	£30,164	£600m

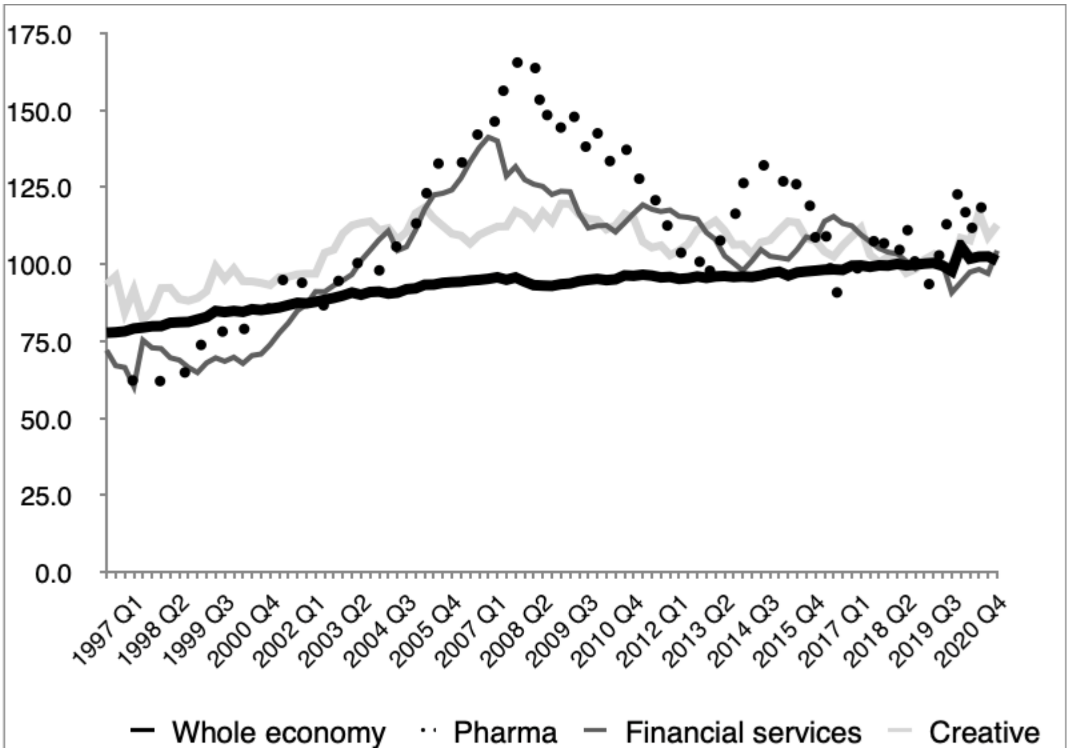
PWC: https://www.pwc.co.uk/industries/pharmaceuticals-life-sciences/insights/the-life-sciences-future50.html & Office for Life Sciences; https://www.gov.uk/government/collections/bioscience-and-health-technology-database-annual-reports; ONS: Blue Book 2023 https://www.ons.gov.uk/economy/grossdomesticproductgdp/compendium/unitedkingdomnationalaccountsthebluebook/2023/supplementarytables;TradeTimeSeries,2024-https://www.ons.gov.uk/economy/nationalaccounts/balanceofpayments/datasets/tradeingoodsmretsallbopeu2013timeseriesspreadsheet ; Creative Industries Jobs Data, 2023 - https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/adhocs/15627jobsinthecreativeindustriesandoccupationsinlondonandallotherregionsoftheuk2010to2021 ; Annual Surveys of Hours and Earnings 2023 https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/earningsandworkinghours/datasets/ashe1997to2015selectedestimatesOLS: Bioscienceandhealthtechnologysectorstatistics,2023-https://www.gov.uk/government/statistics/bioscience-and-health-technology-sector-statistics-2021-to-2022#full-publication-update-history ; Life Sciences Sector Data, 2024 - https://www.gov.uk/government/publications/life-sciences-sector-data-2024 DCMS: Sector Economic Estimates GVA 2022 - https://www.gov.uk/government/statistics/dcms-sectors-economic-estimates-regional-gva-2022 ; Sector Economic Estimates - Trade, 2021, Main Report - https://www.gov.uk/government/statistics/dcms-and-digital-sector-economic-estimates-trade-2021/dcms-sectors-economic-estimates-trade-2021-main-report; Sector Economic Estimates: Earnings 2023 and Employment October 2022 to September 2023 - https://www.gov.uk/government/statistics/economic-estimates-earnings-2023-and-employment-october-2022-to-september-2023-for-the-dcms-sectors-and-digital-sector

omy from 1997 to 2020. That the three sectors have contributed to the broader slowdown post-2008 in trend productivity growth is clear from the chart, with the productivity index declining in each case. This is consistent with other evidence that the biggest contributors to the UK productivity slowdown have been high value, intangibles-intensive sectors (Coyle and Mei 2023, Goodridge and Haskel 2023). Nevertheless, between 2000 and 2020, whole economy labour productivity rose 19 per cent, compared with 53 per cent for pharmaceuticals and 50 per cent for finance.

Life Sciences and Pharmaceuticals

The pharmaceuticals and life sciences sector spans several SIC codes, including the manufacture of basic pharmaceutical products (SIC 21100), preparations (21200) and also biotechnical research activities (72110) and 'other' scientific activities (74909). As with the creative sector, policy documents as well as company activities may refer to a broader or narrow range of these. Although the sector boundary is

Chart 1, GVA per Hour Worked by Sector (Volume Index 2019=100)



Source: ONS (2022) Labour productivity by industry division (2022, January). https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/datasets/labourproductivitybyindustrydivision.

fuzzy, it is intertwined with health policy and the role of the NHS in the UK as a purchaser of products, a valuable environment for trials, and increasingly as a potential source of data for use in research. Not surprisingly, given the role of safety regulation in medicines as well as the outsize importance of government policy decisions in health provision in the UK, the industry undertakes considerable lobbying efforts, which help explain the shape industrial policy interventions have taken over time. Naci & Forrest (2023) summarize these efforts as funding for patient support groups (which can call for the NHS to pay for specific drugs, for example; for clinical commissioning groups; and for Parliamentary interest groups (p22).

Box 1 summarizes relevant policy interventions since 1990. These take three main forms. First, there is a clear and stable regulatory framework. This has been a significant enabler of UK comparative advantage in the life sciences in particular. The extended public and political consultations undertaken by the Warnock Review led to the establishment of the Human Fertilisation and Embryology Authority (HFEA) in 1991, setting a regulatory framework for embryology and genetic research that had societal consent and enabled the UK to operate at the frontier of blue skies and applied research in this area (Harding 2023). The legislation set the HFEA dual aims of patient care and medical innovation (UK Government, 1990). The broader regulatory framework for approving pharmaceutical products and funding them, with the Medicine and Healthcare Products Regulatory Agency, has also remained stable and

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Box 1: Health and Life Sciences timeline 1990-present

- **1990s to 2000**:
  - Clear regulatory framework e.g. HFEA in 1991 set framework for life sciences research; European Medicines Agency established in 1995
  - Healthcare policy and market access: targeted cost-effectiveness of new drugs to support healthcare policy. Led to the National Institute for Health and Care Excellence (NICE), 1999
- **2000- 2010**:
  - Medicine and Healthcare Products Regulatory Agency, MHRA established in 2003
  - Increased public funding for Research; National Institute for Health Research (NIHR) established in 2006
- **2010-2020s**:
  - Cancer Drugs Fund Established in 2011
  - Cell and gene therapy Catapult Centre (across 4 locations) established by Innovate UK
  - MHRA rebranded, 2013
  - Tax subsidy: Patent box 2013
  - Technology transfer and innovation support: attempts at commercialisation spin-outs from R&D, e.g., the Biomedical Catalyst programme 2013 – now under Innovate UK
  - Programmatic interventions beginning in 2012, e.g., establishment of the Cell and Gene Therapy Catapult 2012 and the Medicines Discovery Catapult 2015
  - Increased research support: National Health Research Authority 2015
  - Cancer Drugs Fund Reformed, 2016
  - Public-private partnerships, e.g., Industrial Strategy Life Sciences Sector Deal 2017
  - More programmatic support – PPP Innovative Medicines Fund, 2021; NHS launches Commercial Medicines Framework, 2021
  - MHRA becomes standalone UK Regulator of Medicines, 2021
  - Innovative Licensing and Access Pathway (ILAP) established, 2021

Source: Authors' own

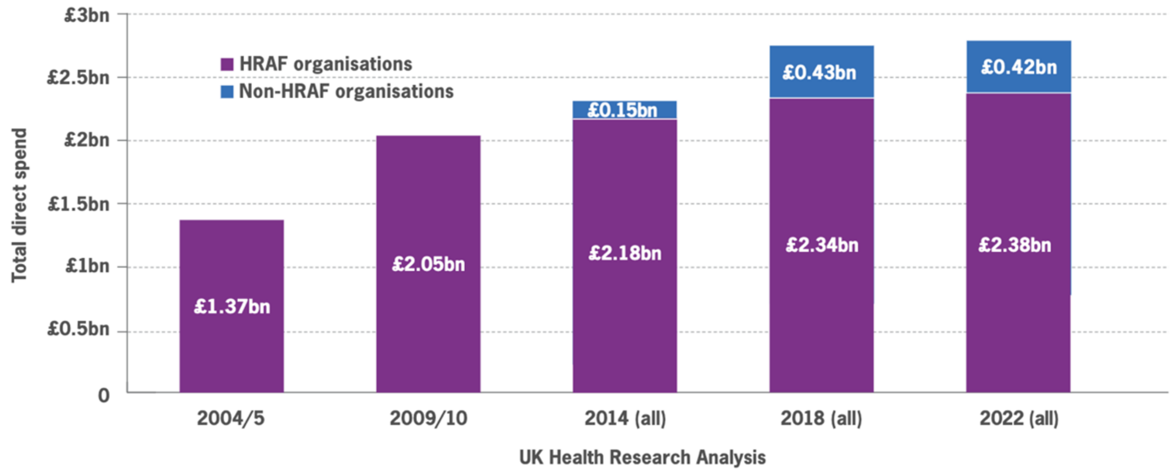
provided researchers and the private sector with a clear operating framework. This is a clear example of the benefits of regulatory clarity and stability in enabling innovation and investment.

The second, and related, intervention has been consistent and significant public funding for research in UK universities, augmented by private funding from charities and foundations such as the Wellcome Trust. Jones and Wilsdon (2018:5) note the scale of the increase in funding for biomedical research since at least 2000: "The share of overall research council spending accounted for by the Medical Research Council (MRC) has risen from 16 per cent in 2004 to 24 per cent in 2015 – a 75 per cent increase in real terms,".

Chart 2 shows the increase over time in health-related research funding. This has brought huge innovations, not least the first sequencing of the human genome by John Sulston and colleagues, announced in 2000, and several UK Nobel Prizes. The continuing research funding has enabled the UK to retain its research lead and to attract and retain private investment in pharma and biomedicine, building on early industrial strengths from ICI in the 1960s onwards and on early intellectual advances, such as Franklin, Crick and Watson's discovery of DNA. The Laboratory of Molecular Biology at Cambridge has recently been singled out as one of the most successful ideas factories ever, producing over a dozen Nobel Laureates (Gebel *et al.*, 2024). One estimate put the annual total economic rate of return on public health research spending in the 20 years to 1995 at between 15 and 18 per cent (Sussex *et al.*, 2016) although – in arguing for a reprioritization of funding away from basic biomedical and life sciences research to research into behavioural and environmental influences on health – Jones and Wilsdon argue that the economic return has diminished since.

A third significant policy tool supporting the sector has been tax relief for private sector R&D and the introduction of the patent box in 2013. Companies registering for the relief pay a lower corporation tax rate of 10 per cent on profits at-

Chart 2: Direct Expenditure on Health-related Research in the UK



Source: The UKCRC Health Research Analysis Forum (HRAF) (2023), a subgroup of twelve large public and charity funders of health research, plus the Association of Medical Research Charities (AMRC. https://hrcsonline.net/wp-content/uploads/2024/04/UK_Health_Research_Analysis_Report_2022_web_v1-1-postpub.pdf

tributable to patented products they have developed. The total value of relief claimed in 2022 was £1.4bn, almost all (94 per cent) claimed by large companies. The tax authority, His Majesty's Revenue and Customs (HMRC), does not publish data beyond broad SIC categories, but manufacturing companies account for over half the claimants and 44 per cent of the relief. The effectiveness of the tax relief in encouraging companies to locate and commercialize their R&D in a particular country has been questioned (Gaessler *et al.*, 2021) but – as with other corporate tax instruments – governments are likely to feel compelled not to diverge too far from practice in countries competing for such investments.

Financial Services

The UK has long had a comparative advantage in financial and related services thanks to the City of London. From the formation of the Lloyds of London insurance market after its early informal beginnings in local coffee houses to innovations such as the idea of discounting (Deringer, 2018), today's City began to take shape in the 17th and 18th centuries. The creation of the Bank of England in 1694 was an important milestone (Kynaston, 2018). In recent times, the growth of the Eurodollar markets through the 1980s paved the way for the major de- or re-regulation in the shape of the 1987 'Big Bang'.

Among other factors, the legislation passed by the first Thatcher Government enabled a substantial shake-up of the traditional market structures, permitted the growth of derivatives markets, opened London more to foreign banks, and paved the way for most building societies to shed their mutual status and list as public companies. The offshore 'Eurodollar' markets moved onshore, and the City grew massively in terms of transactions volumes, jobs, and also net exports. The financial services core has also enabled growth in ancillary professional services businesses such as law and accountancy firms and mergers and acquisitions (M&A) consultancies.

The regulatory and legislative environment is the main focus of many accounts of financial services policies, and has continued to be contested. The Labour Government's decision early in its 1997 term to make the Bank of England independent and responsible for monetary policy drove one rearrangement of the supervisory architecture. In the 1980s the Securities and Futures Authority (SFA) was responsible for oversight of investment firms, and the Bank of England for banks. With the Bank's independence, a new single body, the Financial Services Authority, emerged from the predecessor Securities and Investments Board formed prior to Big Bang.

Unsurprisingly, the regulatory environment changed again in the wake of the financial crisis, with the splitting of responsibilities into the Prudential Regulatory Authority (PRA, prudential regulation of all firms) and the Financial Conduct Authority (FCA, conduct of consumer-facing firms), while the Bank of England regained responsibility for overall financial stability. This complicated institutional history indicates a once a decade major restructuring of the basic regulatory environment, and was accompanied by an increasingly complex set of international rule books, both from the EU and other bodies such as the Bank for International Settlements and Financial Action Task Force.

One of the benefits of Brexit was claimed to be the potential to lift some of the post-2008 regulatory burden on the financial sector, including unpopular (with the City) caps on bonuses. In 2024, the newly-elected Chancellor Rachel Reeves used a speech to signal a tilt away from regulation toward greater risk-taking (HM Treasury, 2024). The overall picture is one of an unstable regulatory environment for the sector.

While the story of regulation since 2008 has largely been one of increasingly tight restrictions, an important exception has been the FCA's introduction of its innovation 'sandbox' for fintech startups and for already-authorized firms wanting to test new technology products. Studies typically find positive effects on the participants on metrics such as ability to raise capital and many other countries have adopted regulatory sandboxes for finance. The innovation remit of the Payment Services Regulator and efforts to enforce competition in UK retail banking through the Open Banking initiative, have probably also helped foster fintech innovation.

As Box 2 indicates, other 'classic' industrial policy supports for financial services have often been overlooked, however. These have included planning reforms enabling the construction of the modern landscape of the City, with large floor spaces for trading floors and the liberation of air rights to build out over public highways and spaces; and the creation in 1981 of the London Docklands Development Corporation. The City – or rather Canary Wharf – has also benefited from infrastructure investments in the Docklands Light Railway (cumulatively over £1bn), the Jubilee Line extension (£3.5bn), London City Airport (£400m), and the Elizabeth Line serving Canary Wharf from towns west of London (£19bn). Other parts of the UK can only weep at the scale of these investments in

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Box 2: Financial Services Timeline 1990-Present

- **Late 80s – early 90s:**
  - Major regulatory shake-up: 'Big Bang', Financial Services Act and Building Societies Act 1986, Building Societies' demutualizations. Securities and Investment Board 1985
  - Planning reform in City of London and Docklands, development support for Docklands, construction boom
  - Infrastructure investment: DLR, City Airport
- **Late 90s to mid-2000s**:
  - Regulatory evolution: Bank of England loses stability and market oversight functions in creation of Securities and Investment Board; SIB morphed into Financial Services Authority (Financial Services and Market Act 2000)
  - Investment schemes: e.g., Venture Capital Trusts, 1995 – targeted at small, high-risk companies
  - Jubilee Line extension
- **Post-2008 crisis**:
  - Regulatory evolution: shake-up of regulators
  - Nationalization of failing banks – subsequent share sales
  - Public funding for R&D in fintech
  - Banking Reform Act, 2013
  - Elizabeth Line opened 2022 (Crossrail)
  - Financial Services and Markets Act 2023
  - Brexit

Source: Authors' own

London's transportation infrastructure.

Creative Industries

In contrast to pharma/life sciences and financial services, the UK's creative industries did enjoy an intentional industrial policy early in the 20th century, but have been the poor relation in terms of policy attention and strategy in recent decades, to the extent that it is the most 'accidental' of the industrial policy examples in this paper. The BBC was established 1922 as the British Broadcasting Corporation, by the Post Office convening private companies such as Marconi to create a commercial rival to RCA and help ensure that the American company did not dominate in the new technology of radio (Coyle, 2015). At that time it was seen as a research and engineering-centric company; while subsequent BBC Royal Charters have all included a core engineering R&D function, this has shrunk over time although it has remained an important participant in areas of broadcasting and internet research, and in international standards-setting in broadcast and online technologies.

The radio and then television markets subsequently grew, with the UK landscape changing when the television Act of 1954 established the Independent Television Authority, later known as the Independent Broadcasting Authority, and the first commercial channels launched in 1955. Mrs Thatcher's Government further liberalized the broadcasting market in 1990.

Other pre-1990 interventions were the establishment of the British Film Institute Production Board in 1964 (it was folded into the UK Film Council in 2000, which in turn was closed down in 2011) to commission experimental and indeed uncommercial films; and the launch in 1982 of publicly-owned Channel 4 & S4C (in Welsh) to stimulate innovation in the independent production sector. These broadcasters are purchasers not producers, and hence their funding (advertising for Channel 4 and part of the BBC licence fee for S4C) is a form of advance market commitment (Kremer *et al.*, 2020).

One notable intervention with a lasting impact on the UK economy was the BBC's commissioning of the BBC Micro in 1982, as a tie-in to a TV programme (The Sil-

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Box 3: Creative Sector Timeline 1990-Present

- **1990 to 2000**:
  - The Broadcasting Act 1990: deregulation of the broadcasting industry
  - BBC and Channel 4 provide advance purchase commitment and training for independent sector
  - Establishment of National Lottery, 1994, provided significant funding for independent producers
  - Creative Industries Task Force established, 1997
- **2000 to 2010**:
  - First set of tax reliefs: Film Tax relief in 2007
- **2010 to 2020s**:
  - Creative Industry Council established 2011
  - More tax reliefs: High-End Television Tax Relief 2013, Video Games Tax Relief 2014
  - Screen Skills created in 2018

Source: Authors' own

icon Factor, followed by ITV's The Might Micro in 1983) explaining computers (Radcliffe and Salkeld 1983). The commission to produce the machines, which supported coding in a version of Basic, was won by Acorn Computers in Cambridge, the seed from which today's chip design giant ARM developed.

Even more significant, however, was the development of a generation of software developers and the highly successful UK games industry out of the new coding enthusiasts who bought the machines. An early blockbuster game was Elite, created by two Cambridge students. The UK's early strengths in games development were cemented by some new university courses, such as those developed at Abertay University. The BBC undertook the exercise as part of its education mission, specified in every one of its Royal Charters, and had a grant of £10,000 from the (then) DTI's Electronic Applications Division. Since that intentional start, however, there has been little systematic strategic policymaking for the games sector, the computer software sector or the rest of the creative industries more broadly (Tsang 2021). The UK's games and software sectors are fragmented with few large companies, and whose trade surpluses are small (Mandys & Coyle 2024).

As the timeline in Box 3 shows, there have been piecemeal policies across the creative sector, such as small tax reliefs and – importantly – funding provided through the National Lottery. On the contrary, although on some definitions the creative industries account for as large a share of GDP as do financial services, successive governments have cut basic arts funding (which can be seen as the equivalent of R&D for the cultural industries), downplayed the importance of arts education in schools and universities, reduced public funding in real terms for the BBC, and kept the future status of Channel 4 in doubt. Broadly speaking, although (as Table 1 shows) various industrial policy statements have included the creative industries as a key sector, Box 3 indicates a paucity of policy interest, with a focus on tax reliefs for the private sector and deregulation.

The consequence of this market-first orientation in the creative industries has been – apart from constant funding pressures – a failure to deploy effectively the BBC's role as an engine of industrial policy for the sector, and an opening of UK broadcast markets to overseas providers. While this may benefit consumers, it risks undermining UK-based skills and supply chains.

In addition to its engineering R&D in relevant technologies (including for example the first deployment of long-form video on demand and implementation of high definition television), the BBC is a large commissioner and purchaser of UK radio, TV, online and music output, with regulatory requirements to purchase from suppliers around the UK. It is an important funder of the sector's skills body and provides skills and experience for large parts of the rest of the sector. R&D funding, advance purchases and skills provision are all classic industrial policy tools.

Moreover, successive Governments' neglect has not been benign. Political attacks and funding cuts have made it increasingly difficult for the BBC and Channel 4 to play these policy roles, as even some of their commercial rivals accept. One specific policy decision with adverse consequences was the Competition Commission's 2009 decision to ban for 5 years a joint venture between the five UK broadcasters to provide a long-form video streaming platform ('Project Kangaroo'). This paved the way for Netflix to enter that market and become the UK's biggest broadcaster. The supply-side implications of the decision for the UK's production base did not feature in the reasoning for the decision (Coyle 2024).

Discussion

Of these three examples, the sector that comes closest to a 'classic' industrial policy, acknowledged as such, is pharmaceuticals and the life sciences. It featured in almost all the iterations of formal industrial policy described in Table 1. One explanation for this may be the lobbying effectiveness of the pharma industry (Naci & Forrest 2023; Abraham 2002; Rickard and Ozieranski, 2021). But the sector has historic strengths dating at least back to the 1960s, both in research and in industrial production.

The financial services sector is not generally regarded as the beneficiary of a sector-based industrial policy, in part because of the tendency in the debate to focus on manufacturing. It has nevertheless has also been consistently seen as an area of UK strength, with a long history of innovation and comparative advantage dating back to at least the 17th century. It too wields significant lobbying power (Culpepper, 2014; Bell and Hindmoor, 2015, 2017) while governments are also mindful of the power of the financial markets to make or break their macroeconomic policies. However, the debate about policy for the industry focuses on regulatory design and institutions, whereas as we have noted it has also benefited from other classic industrial policy tools such as significant infrastructure investment. Given the instability of the regulatory framework, other aspects of the policy environment may have been important in cementing the UK's status as an international financial centre.

The creative sector has increasingly come to be seen as an area of economic strength for the UK but it is more disparate, arguably lobbies less effectively, and the BBC in particular has increasingly become a focus of culture war politics. So while the sector benefited from an explicit industrial policy in the early 20th century, and was a focus of deregulatory policies from the 1960s and especially the 1980s on, government policies have become progressively less supportive of the sector over time. Although it is comparable in scale to the financial services sector in terms of GVA, jobs and trade, it does not have equal status in terms of policy priorities such as tax reliefs or public R&D. Indeed, recently government policies have in some ways become actively hostile to the sector, although the current Labour government has so far taken a different tone.

What the three examples have in common is that the various policies supporting them have not formed part of a conscious strategic framework, with interventions linked to specific identified needs. As Figure 1 indicated, the differing economic welfare rationales for not 'leaving it to the market' point to different subsets of policy instruments. While public support for basic R&D due to knowledge spillovers is indeed an appropriate instrument in the case of life sciences, as noted questions have been raised about whether or not there is now too much funding relative to other research areas.

Meanwhile the important role of the UK's regulatory environment has not been fully acknowledged; it will be important to maintain the stability of the regulatory framework and to develop a similarly clear and stable set of rules for health data use in the age of AI. In addition, other sectoral needs have not been met. For example, companies often complain of skill shortages at the mid-skill level, such as lab technicians; from 2010-2020 the highest growth in demand in scientific and technical companies was for employees with undergraduate and higher apprenticeship qualifications rather than PhDs (Royal Society, 2022). This too calls for a policy addressing the need for a public good, as in Figure 1, and a strategic framework might more easily enable joining up of financial incentives, R&D and skills needs – as without the latter, the impact of government spending or tax breaks will be more limited.

In the case of financial services, the regulatory environment has by contrast been unstable over many governments, understandably so post-crisis. But the framework continues to be debated and it seems likely to remain contested. There are also questions about the appropriate regulatory framework for fintech innovations, and the balance between enabling innovation and protecting consumers.

The debate also ignores the important role of planning policies and infrastructure provision. The question here seems to concern the societal economic return to what has in fact been substantial public subsidy to the sector (even ignoring the public finance cost of bank bailouts and the ultimate cost of the QE programme). As a number of authors have pointed out (Christophers 2013, Coyle 2014), the construct in the national accounts of 'financial intermediation services indirectly measured' imputes valued added to speculative trading by the sector. Of the three sectors discussed here, it is by far the most successful net exporter, but it would not be unreasonable to consider its 'true' ratio of GVA to GDP to be lower than the 7 per cent recorded in the national accounts. An intentional policy framework would investment and regulation to better outcomes for society including productivity and potentially regional economic outcomes. For example, should infrastructure investments favouring the sector occur outside the City of London and Canary Wharf, in cities such as Birmingham, Edinburgh and Manchester?

When it comes to the creative sector, there is, in recent decades, a sense that its success has come about despite stated government support rather than because of it. Although a varied sector, including broadcast, games, software, publishing, heritage and the arts, with a share of GDP and numbers employed similar to financial services, public funding has been progressively reduced in real terms. The success of public interventions such as Channel 4 or the BBC Micro does not feature in political rhetoric; on the contrary, successive Conservative Governments sought to undermine the case for any government role at the same time as enabling and lauding commercial activities – even though these often have foreign providers without a commitment to the UK supply chain.

Nevertheless, the UK's creative sector is, like the others, an economic success story. Understanding interventions the sector as an important area of economic policy would help maximize its potential productivity, which also has an important regional dimension.

Given that these are successes, the argument here concerns the counterfactual: how much more successful might they have been with an intentional and stable industrial policy framework, with interventions targeted to identified market failures? accident. We argue that there are (at least) two channels through which industrial policy by design would have enabled higher productivity in these sectors, as compared with the reality of accidental industrial policies.

One of these is *reduced investment risk due to reduced policy uncertainty:* a sustained industrial policy would encourage a more stable tax and regulatory environment, including by making explicit the political choice made with regard to trade-offs. For example, in contrast to the life sciences, the financial services sector could have experienced less regulatory upheaval, offering firms more clarity about the policy trade-offs between competition, innovation and consumer protection or financial stability. Similarly, if there had been a sustained industrial policy focus on the creative industries, with less policy churn with regard to tax breaks or skills policies, or simply a greater awareness among politicians of the sector's economic scale and importance, the UK could instead have grown a more export-oriented sector with larger producers rather than the current fragmented supply base of small independent suppliers and freelancers.

Policy churn is an often-noted weakness of the UK political system, and there is cross-country evidence that policy uncertainty reduces investment (Davis, 2019). Industrial policy offers a potential framework for reducing policy-related uncertainty, both by reducing churn and through classic instruments such as standard-setting and advance market commitments.

A second channel is the potential to realize spillovers through co-ordination. High value and knowledge-based sectors are characterized by knowledge spillovers. These can take the form of agglomeration in certain locations, given the evidence on the continuing importance of in-person links and thick labour markets for specialist skills (e.g. Atkin *et al.*, 2022, Giroud *et al.*, 2024). The massive infrastructure investment in London's financial services is an implicit recognition of the power of agglomeration. With an intentional strategy, UK Governments might also have considered more carefully the location of the major infrastructure investments and planning reform, to accelerate the development of secondary financial services locations in the UK. With a greater focus on labour market spillovers and training provision life sciences and pharmaceuticals could have fewer mid-level skill shortages or labour market mismatch. The keystone role of the public service broadcasters in the creative industries could, in a counterfactual world, have been used through R&D, training and clustering to have delivered a larger sector, exporting more. The positive impact of the BBC's 2007 decision to relocated a large chunk of its services and activities to Media City in Salford suggests the positive scope for such policies (Nathan *et al.*, 2024).

Labour reallocation from lower to higher value sectors encouraged by policy interventions could also contribute to improved aggregate productivity outcomes. Employment has grown in each of the three cases considered here, although other work has found that the contribution of labour reallocation effects to recent UK productivity performance has been limited (Coyle & Mei 2023).

Policies affecting business decisions cannot avoid having an impact on the supply side of the economy and thus on levels of productivity; acts of omission are choices, just as much as positive decisions. Although the counterfactual outcomes are necessarily speculative, the political revival of interest in industrial policies argues for making the most of the ones we already have, in the context of a more intentional or strategic approach to economic policy at a time of significant technological and geopolitical transition.

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How Does Industrial Policy Impact Output, Hours and Productivity? The Canadian Experience

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Abstract

The article looks at the Canadian experience with industrial policy, and whether those industries that have been the principal focus of industrial policy have performed better than comparable sectors. It outlines the history of industrial policy in Canada and examine the empirical performance of four sectors: steel mills, aluminum smelting, auto assembly and aerospace. It finds that while the aluminum industry has performed better than comparable industries in terms of output, total hours worked and productivity, the same is not true of the other three sectors, which have had a relatively disappointing performance. While the analysis cannot unequivocally prove that industrial policy impact positively or negatively on productivity growth, it acknowledges the possibility that performance could have been worse without such policies. The article also highlights that industrial policy can maintain higher overall productivity by supporting high-productivity industries, preventing their decline.

Industrial policy is definitely having a moment. The Biden administration made huge investments in chip manufacturing through the CHIPS Act and in Green Technology through the Inflation Reduction Act. In Canada, as we shall discuss below, the Trudeau government has promoted industrial policy across a broad swathe of the economy, for example with its Superclusters program. The European Union also has also embraced industrial policy (EU, 2024). Even the OECD, which has historically been skeptical of many government interventions in markets, has concluded that industrial strategies can be legitimate (OECD, 2022).

However, the literature on the actual impacts of industrial policy is surprisingly

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thin (Lane, 2020), particularly when it comes to some key economic variables of interest such as output, hours worked or productivity—perhaps most important of all productivity given weak growth growth in this variable in recent years in many advanced countries.

In this article we try to understand the economic impacts of industrial policy by looking at the Canadian experience. Canada has had some sort of industrial policy almost since it was founded in 1867, and even during the 1980s and 1990s, when industrial policy had very much fallen out of fashion in the Western world, Canadian governments, both federal and provincial, continued to provide support to what were perceived as key sectors of the economy. By comparing the performance of those sectors that have been the main focus of industrial policy in recent years—autos, aerospace, steel and aluminum—with comparable sectors, we try to see if industrial policy in Canada in recent years has had a discernible impact on productivity in those sectors, either positive or negative.

Before embarking on an analysis of industrial policy, it is worth beginning with clarity about what set of policies we are engaged in. While the OECD defines industrial policy as "interventions intended to improve structurally the performance of the domestic business sector," (Criscuolo *et al.*, 2022) we view this as too broad, as this definition would include "horizontal" interventions such as education policy which are generally not targeted to particular sectors (even though they may affect some sectors more than others). Rather, what we are concerned with here is "vertical" interventions that are explicitly intended to favour a particular industry sector.

It should be noted straight away that there are many similarities between industrial policy and regional economic development policy—which uses many of the same tools. There is also a close relation to trade policy, which requires a view on what level of protection a given industry sector should enjoy. We nonetheless focus on what might be termed classic industrial policy, which generally relies on various kinds of subsidies to assist particular industries, without any explicit regional restrictions.

The rest of the article is organized as follows. We begin by sketching the evolution of industrial policy in Canada, at both provincial and federal levels, focussing on four industries that have received particular attention from policymakers: steel mills, aluminum smelting, auto assembly and aerospace. We then look at the performance of output, hours and productivity in these four industries in recent years. We compare performance of each industry to closely related industries and to manufacturing overall. We then offer some conclusions.

Evolution of Industrial Policy in Canada

Industrial policy in Canada has long been bound up with the broader question issue of Canadian national identity. Canadia has traditionally sought to resist the economic pull of first the British Empire—not wanting to be simply "hewers of wood and drawers of water", exporting natural resources to be processed in the United Kingdom in return for manufactured goods—and then the United

States—resisting complete economic integration which, it was feared, would lead to political integration. Thus Canadian policymakers, almost since Confederation in 1867, have sought to develop and protect manufacturing industries.

Initially this was done largely through tariffs, beginning with Sir John A. Macdonald's National Policy of 1879; Government procurement during the First and Second World Wars gave an additional boost to this policy objective, as governments expanded industrial capacity to meet wartime needs for military equipment, following which the capacity was retooled to meet civilian needs. Strategic industries, particularly in transportation, were nationalized (CN Rail in 1919), or created by government if they did not already exist (Trans-Canada Airlines in 1936, which subsequently became Air Canada).

It should be noted that this policy approach has often been controversial, particularly in Western Canada, which is much more reliant on resource exports, and which therefore has tended to favour less protection and greater access to export markets.

This interventionist approach continued after World War Two (Ciuriak and Curtis, 2013), and intensified during the 1970s when the Canadian economy, like so many others in the Western world, began to hit significant economic headwinds. When the Mulroney government entered power in 1984 it inherited an economy with significant tariffs on manufactured goods, high levels of government ownership (including CN Rail and Air Canada in transportation, Petro-Canada in energy, and De Havilland Canada and Canadair in aerospace), and price controls, most notably on energy (the National Energy Policy) but also on dairy and poultry products (supply management).

The Mulroney government set about energetically dismantling much of this architecture. Most state-owned industries were privatized (including the above-named companies), the National Energy Policy was scrapped (although not supply management), and the government negotiated a free trade agreement with the United States that eliminated most tariffs with Canada's largest trading partner, destination for four-fifths of Canadian exports.

The explicit aim of this suite of policies was to make the economy more efficient, to ensure that price signals would guide economic decisions, and to transform Canada from a "Branch Plant Economy", where foreign-owned factories produced goods for the Canadian market (in order to get around the tariff wall), into an export-oriented economy that could be efficient by producing at much larger scale. Allied to significant tax reforms, including replacement of a manufacturers' sales tax with a VAT, the policy agenda was explicitly free market, with, rhetorically at least, little room for industrial policy as we have defined it.

Industrial Policy – 1986 to 2015

However, this move to economic liberalization did not mean the complete end of industrial policy. The recession of the early 1980s had led to large scale unemployment, particularly in traditional manufacturing sectors, and in an environment of increasing mechanization, including robots, and competition from developing countries, particularly ChinaJapan, governments were under increasing pressure to protect blue-collar manufacturing jobs, particularly in unionized industries with relatively high rates of pay. While Canada did not necessarily have “an articulated industrial policy per se” (Ciuriak and Curtis 2013), government intervention began to increase again. Four sectors in particular were the main focus of government attention from the mid 1980s until the arrival of the Trudeau government in 2015—aluminum, steel, aerospace, and motor vehicle manufacturing. We shall go through each of them in turn.

Aluminum Smelting

The bulk of Canada's aluminum smelting industry is in the province of Quebec. In 1987, that province instituted a scheme that linked the price of electricity from its provincially-owned power company, Hydro-Quebec, to the world price of aluminum. Electricity is a key input into the production of aluminum, and the scheme helped attract three new companies into Quebec (Aluminium Association of Canada, 2024). Since its inception the pricing scheme has resulted in implicit subsidies of billions of dollars to the aluminum smelting industry (Yakabuski, 2022). In 2019, the (OECD, 2019) found that Canada had the third highest level of support to its aluminum industry, behind China and Bahrain .

Steelmaking

While industrial policy in the aluminium industry was undertaken for essentially offensive reasons, to lure new companies and new investment into the province of Quebec, policy in the area of steel has been much more defensive and ad hoc. The industry is largely concentrated in the province of Ontario, where it helps supply key downstream manufacturing industries, particularly the auto sector. Intense competition from subsidised producers, particularly in China, has made life difficult for steelmakers, and in the early 1990s the Ontario government was forced to bail out one of the largest companies. In the wake of the 2009 financial crisis, federal support was forthcoming through the newly created Federal Development Agency for Southern Ontario.

Aerospace

Like steel, the aerospace sector is one where countries have long protected their domestic industries, partly for economic and partly for security reasons. In the aerospace sector, for example, the Brazilian company Embraer, initially state-owned, began to be a serious competitor for Canadian companies such as Bombardier in the 1990s, and the two companies embarked on a long battle at the World Trade Organization (WTO) over subsidies, which resulted in both countries being found to have subsidized their industries.

A key element of federal support for aerospace is the Industrial and Regional Benefits (IRB) policy (now called the Industrial and Technological Benefits Policy), which was introduced in 1986. It requires companies winning defence contracts to undertake business investments in Canada in advanced manufacturing (generally in the defence and aerospace sector) equal to the contract value (Canada, 2015). Thus if a company wants to undertake some activities offshore to fulfill a contract, it must offset that loss to the Canadian economy by undertaking other work in Canada, perhaps to fulfill a foreign order. This provides a strong incentive for a company to undertake the work in Canada.

While innovative, the IRB policy was not felt to be enough, and in 1996 the federal government launched Technology Partnerships Canada (Canada, 1996), which provided matching funds for investments in high technology products and processes, and which was squarely aimed at the aerospace sector, although environmental technologies and advanced manufacturing were also mentioned. (It is this program which led to Canada being taken to the WTO as mentioned above).

With a change in federal Government, TPC was wound down in 2006 and replaced by the Strategic Aerospace and Defence Initiative (SADI). This program provided repayable contributions to support research and development in the aerospace, defence and security sectors (Canada, 2014). As an example of its activities, in 2017 the federal government announced a major contribution to the development of two new aircraft by Bombardier (Canada, 2017a) (one of which—the C-series—was subsequently sold to Airbus which produces the aircraft in Canada).

Automotive

The automotive industry and its associated network of suppliers, is one of Canada's most important industries. However, like other industries mentioned here it has faced competition from often subsidized competitors, in this case from the United States. In the 1980s southern US states such as Kentucky and Tennessee began to offer large incentives to foreign automakers to build new factories in their states (Minchin, 2021). These states were joined in the 1990s by Alabama and South Carolina, and by the early 2000s even Michigan was offering significant incentives in the form of tax credits, infrastructure support and worker retraining.

The Ontario government, where most of Canada's auto sector is located, responded with financial incentives of its own to attract and keep investment in the province. The province was successful in attracting two major Japanese manufacturers, Honda and Toyota, to Canada.

The pressure to help the auto sector became particularly intense during the Great Financial Crisis of 2008–2009, when the big three American automakers—all of which had facilities in Canada—where faced with bankruptcy. Although Ford ultimately managed to make it through without government help, General Motors and Chrysler (as it then was) were not so lucky. The Canadian government participated in the US government's bailout of the two companies with a $9 billion contribution (Financial Post, 2014).

The federal government added to this temporary support by launching the Automotive Innovation Fund (AIF) in 2008, which provided contributions for large automotive R&D and manufacturing projects.

Industrial Policy since 2015

The election of the Liberal government in 2015 marked a significant shift in both the rhetoric and substance of industrial policy. Instead of being largely focused on particular sectors such as autos, or aerospace, the new government made clear its desire to actively support businesses across the economy by helping them to become more innovative. Indeed, the Department of Industry was renamed the Department of Innovation, Science and Economic Development (Financial Post, 2015). Innovation was seen as closely linked to clusters: "dense areas of business activity that contain large and small companies, post-secondary institutions and specialized talent and infrastructure—energize economies and act as engines of growth (Canada, 2017b)."

The 2017 Budget laid out the two key components of this approach. The first was the Strategic Innovation Fund, which combined earlier sector specific programs—including SADI and the AIF, into one entity which, while continuing to support the aerospace and auto industries, would also be open to other sectors of the economy. The second component, even more of a break from the previous government's policy approach, was the Superclusters initiative (subsequently renamed Global Innovation Clusters). Each cluster is focused on a specific sector in a specific region, and is an attempt to bring business, government and academia together in order to decide on funding for innovation-focused projects where contributions from government would be matched by contributions from business. (Owens, 2022).

Following a competition, the government announced five region/sector pairs: marine industries in Atlantic Canada, artificial intelligence in Quebec, advanced manufacturing in Ontario, protein industries in the three Prairie provinces, and digital technology in British Columbia. While critics were quick to note that the government was unable to resist giving each region of the country (apart from Canada's sparsely populated north) its own supercluster, what is notable for our purposes is the government's willingness to expand the government's footprint well beyond the sectors that had traditionally been the focus of industrial policy in Canada.

In recent years the policy approach has evolved to place much greater emphasis on "clean" technology that will help Canada meet its greenhouse gas emissions objectives. The 2021 Budget announced a substantial increase in money for the SIF, three-quarters of which was for a "net-zero accelerator", to help industries decarbonize and develop clean technology (Canada, 2021).

It is important to note that the expansion of industrial policy under the Trudeau government has not meant that industries such as autos, steel and aerospace are no longer receiving support. On the contrary, given their political salience, the government has been careful to ensure that support has continued. Indeed, in 2021, the government announced additional support to the aerospace sector, and the government has provided, along with the provinces of Ontario, large sums of money for electric vehicle battery manufacturing (Parliamentary Budget Office, 2023).

Industrial Policy: What Do We See Empirically?

Table 1: Key Indicators for Industries of Interest 2019.

	Share of Total Hours	GDP per Hour($)	Hourly Wage ($)
Manufacturing	100	68.8	41.7
Primary Metals	3.9	96.1	57.4
Steel Mills	1.1	72.2	59.3
Aluminium Mills	0.8	137.2	59.3
Transportation Equipment	13.6	74.1	49.9
Motor Vehicle Assembly	2.8	81.7	58.4
Aerospace	3.7	89.9	56.7

Source: Statistics Canada: Table 36-10-0480-01
Note: GDP per hour and hourly wage are in nominal dollars.

Industrial policies are usually justified as increasing growth, increasing (or at least safeguarding jobs) and increasing productivity. In Budget 2017 for example, the Canadian government introduced its broadening of industrial policy by proclaiming its desire for

> "Dynamic, globally connected firms [that] will propel clean economic growth, increase Canada's productivity and support well-paying jobs for the middle class."

(Canada 2017b).

What has been the actual impact of the various industrial policies we have outlined above on these economic variables of interest, in particular output, hours and labour productivity?

Our empirical strategy will be to compare the four sectors where industrial policy has been the most active, to aggregate manufacturing in Canada from 1989 to 2019. The four sectors correspond to the following four digit manufacturing industries: steel mills (BS3311); aluminum smelting (BS3313); motor vehicles (BS3361); and aerospace (BS3364).

We also compare steel mills and aluminum smelting to the overall primary metals sector: the other constituent industries in the primary metals are steel products, foundries, and other non ferrous metal production and processing. For motor vehicles and Aerospace, we also compare to the overall transportation equipment sector: the other constituent industries in that sector are motor vehicle parts, railroad rolling stock and shipbuilding.

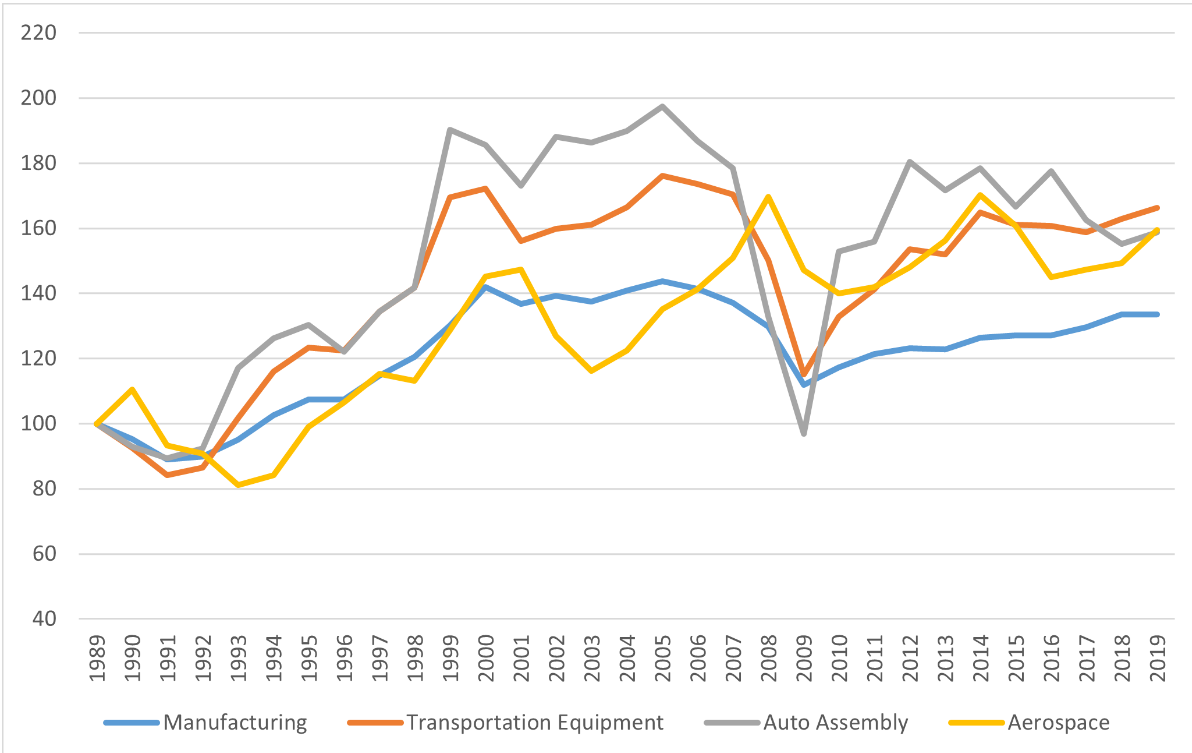
We should note that the motor vehicle parts sector has also been the recipient of some government support, particularly from the AIF, although it did not benefit directly from the 2009 bailouts, or the incentives to attract or maintain auto assembly plants that were instituted to respond to US incentives.

We begin in 1989, a cyclically neutral year. We stop in 2019 to avoid having to deal with the impacts of COVID and associated supply disruptions, which would overwhelm any impact from industrial policy. Furthermore, as we have seen, federal government industrial policy increasing broadened out after 2016 and the introduction of the Supercluster program and the SIF, and particularly in 2021 with the shift on focus to Net Zero.

Description of the Four Industries of Interest

We begin our empirical analysis by looking at the basic characteristics of the four industries of interest. Table 1 shows the

Chart 1: Real Output in Manufacturing, Transportation Equipment, Motor Vehicle Assembly and Aerospace 1989-2019 (1989=100)



Sources: Statistics Canada Tables 36-10-0305-01; 36-10-0480-01.

share of total hours, nominal GDP per hour, and nominal hourly wages per hour (on a total compensation basis) for manufacturing, the sectors of primary metals and transportation equipment, and the four subsectors.

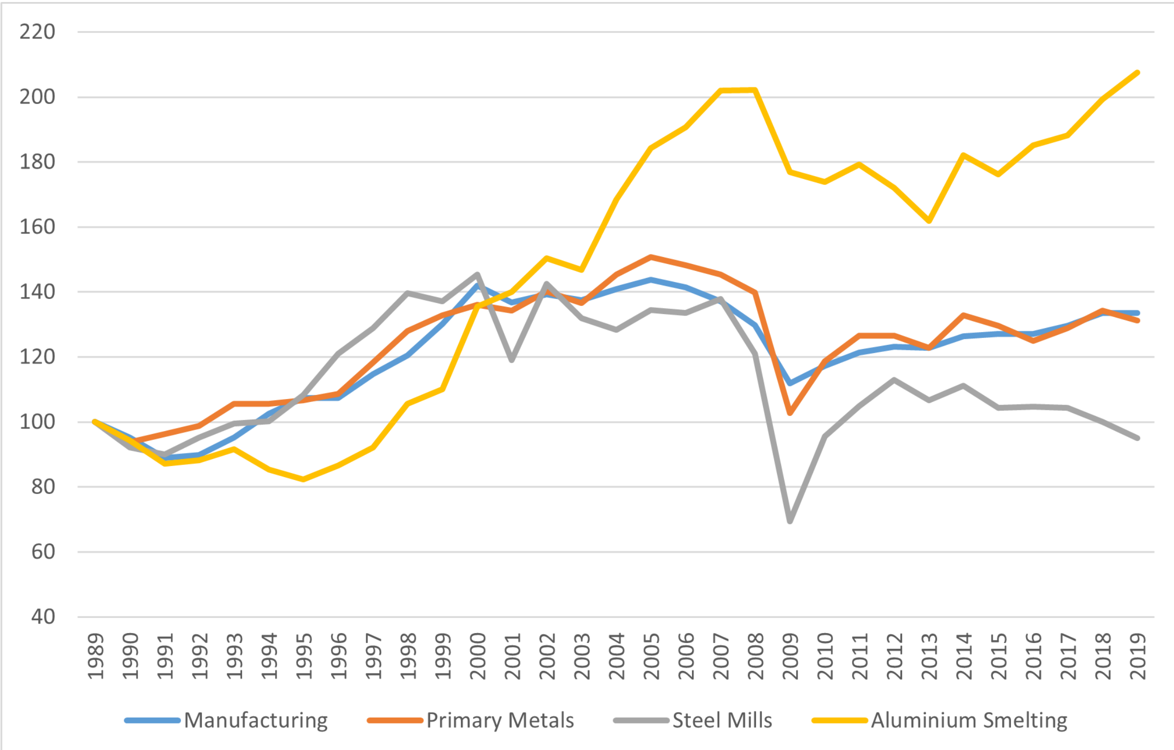
We can see that labour productivity is above average for manufacturing in all four industries, although in the case of steel mills the difference is not large ($72.2 dollars per hour, compared to the average for manufacturing at $68.8). Motor vehicle assembly and aerospace are well above both the manufacturing average and the average for transportation equipment as a whole. Turning to hourly wages, we can see that these are very similar across the four industries—ranging from $57.7 per hour to $59.3 per hour, well above the manufacturing average of $41.7 per hour. This wage premium helps explain to the enduring political popularity of preserving or creating jobs in these sectors.

Performance of Output

We now look at the actual performance of the four industries, beginning with real output. Chart 1 shows real output (defined as real value added) for motor vehicle assembly and aerospace.

We see that the output of the motor vehicle assembly and aerospace sectors have grown faster than manufacturing as a whole—by 2019 both were 59 per cent above their 1989 levels, compared to 33.5 per cent above for manufacturing. However, neither sub-sector grew faster than

Chart 2: Real Output in Manufacturing, Primary Metals, Steel Mills and Aluminum Smelting, 1989-2019 (1989=100)



Sources: Statistics Canada Tables 36-10-0305-01; 36-10-0480-01.

the overall transportation sector, which grew 66 per cent over this period.

Turning now to the other two industries, Chart 2 shows real output for steel mills, aluminum smelting, the overall primary metals sector and total manufacturing.

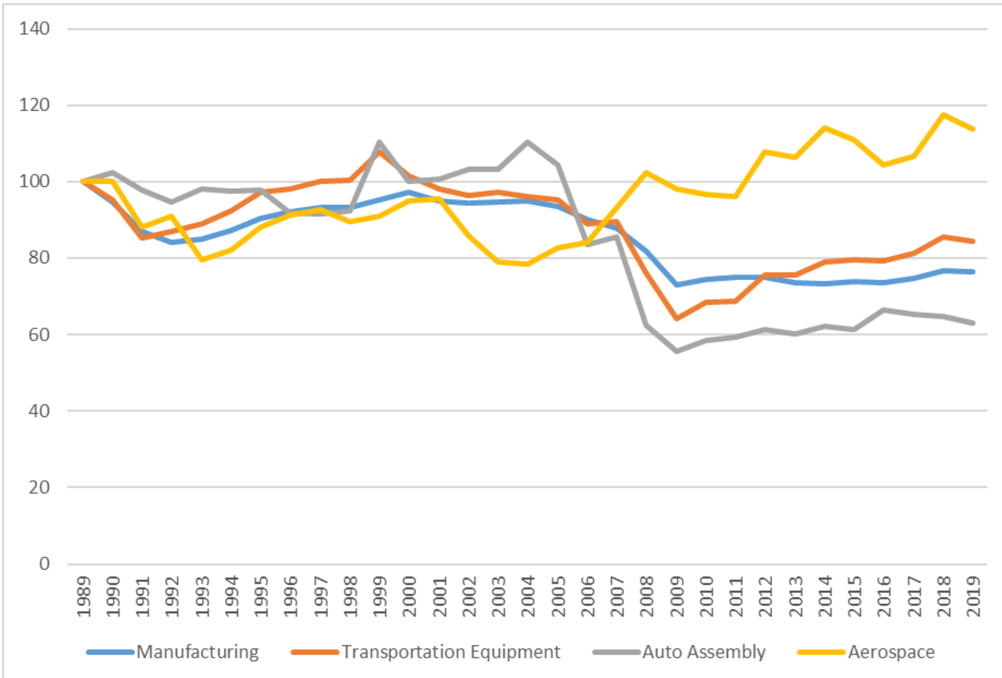
We can see that the two subsectors have had a very different performance. Aluminum has done significantly better than either manufacturing or the whole primary metal sector, having grown by 110 per cent since 1989, compared to 33.5 per cent for manufacturing and 31 per cent for primary metals. However, steel mills have underperformed, with output shrinking 5 per cent. Thus only aluminum smelting has outperformed both manufacturing as a whole and its overall sector.

Performance of Hours Worked

As we discussed above, higher real output is rarely the only goal of industrial policy: rather, another goal is to increase or safeguard highly paying jobs. In this section we compare the performance of hours worked across the four sub-sectors. Chart 3 shows this measure for overall manufacturing, the transportation equipment sector, and the auto assembly and aerospace sectors.

It is evident that the two subsectors have performed very differently. In the aerospace sector, hours worked weakened between 1989 and 2004, falling to 78 per cent of its 1989 level, before climbing to 13 per cent above its 1989 level in 2019. Auto assembly, in contrast, saw hours worked

Chart 3: Hours Worked in Manufacturing, Transportation Equipment, Motor Vehicle Assembly and Aerospace, 1989-2019 (1989=100)



Sources: Statistics Canada Tables 36-10-0305-01; 36-10-0480-01.

rise to 10 per cent above its 1989 level by 2004, only to decline rapidly to 56 per cent of that level by 2009, and then recovering only very slightly, to 63 per cent in 2019. The overall transportation equipment sector saw a decline as well, but only to 84 per cent of 1989 levels, slightly above the 76 per cent of manufacturing as a whole.

Turning to the primary metals sector, Chart 4 shows the hours worked for this sector, manufacturing overall, and the two subsectors of interest: steel mills and aluminum smelting.

As with real output, the two subsectors exhibit quite different behaviour. Hours worked in steel mills declined significantly, so that by 2019, the sub sector was only at 40 per cent of 1989 levels, compared to the primary metals sector as a whole, at 59 per cent, and manufacturing at 76 per cent. On the other hand, hours worked in aluminum smelting grew steadily between 1992 and 2008, declining subsequently, but still relatively healthy at 90 per cent of 2019 levels.

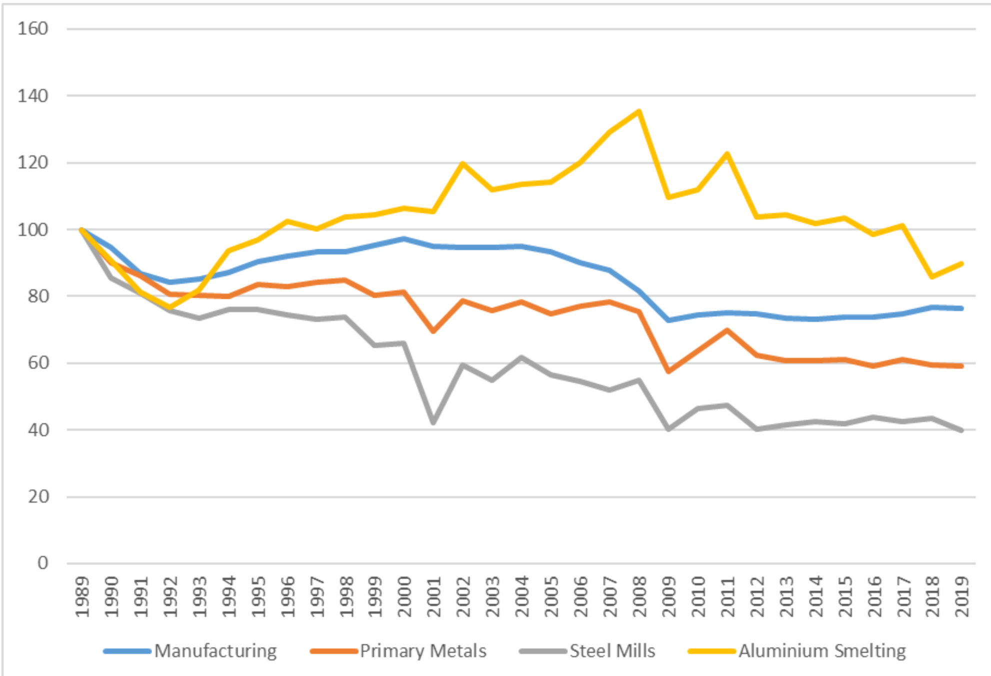
Thus only the aerospace sector has seen growth in employment, although aluminium smelting has done better than manufacturing as a whole. Both the auto assembly and steel mills sectors have done very poorly.

Performance of Productivity

We now turn our attention to labour productivity. Chart 5 illustrates the performance of manufacturing as a whole, the transportation subsector, and the two subsectors of interest.

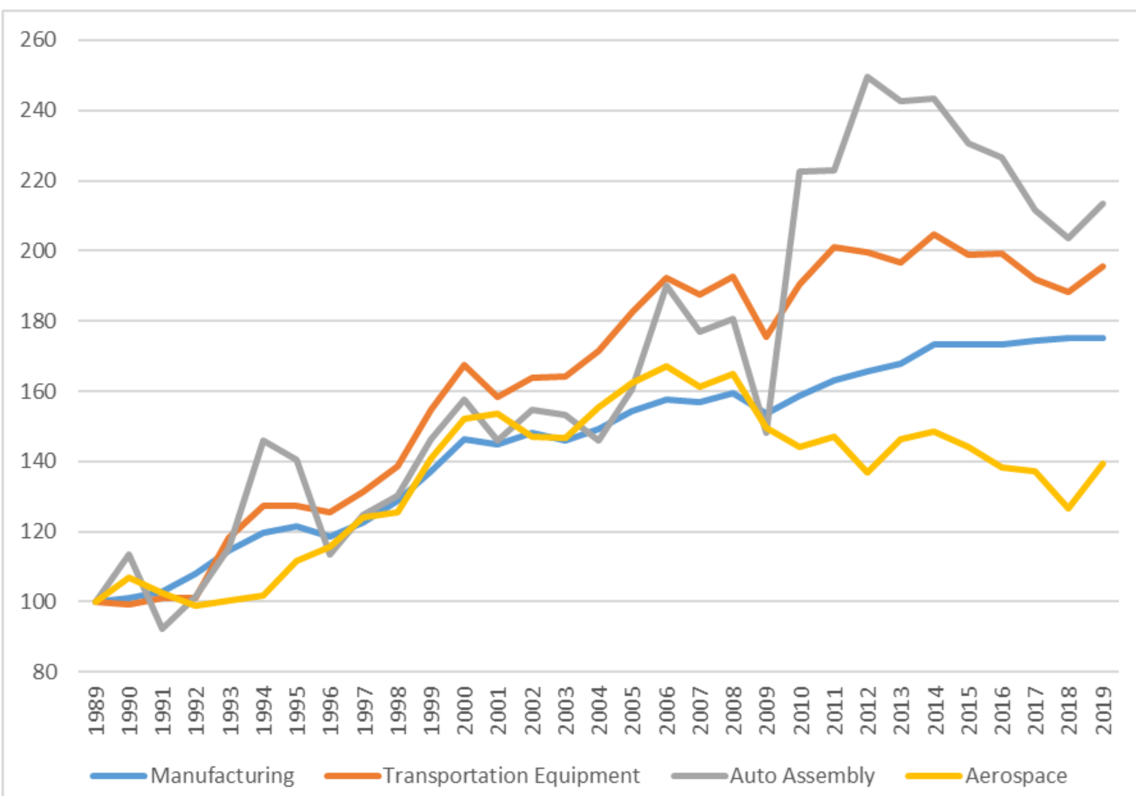
Here we can see that productivity, mea-

Chart 4: Hours Worked in Manufacturing, Primary Metals, Steel Mills and Aluminum Smelting 1989-2019 (1989=100)



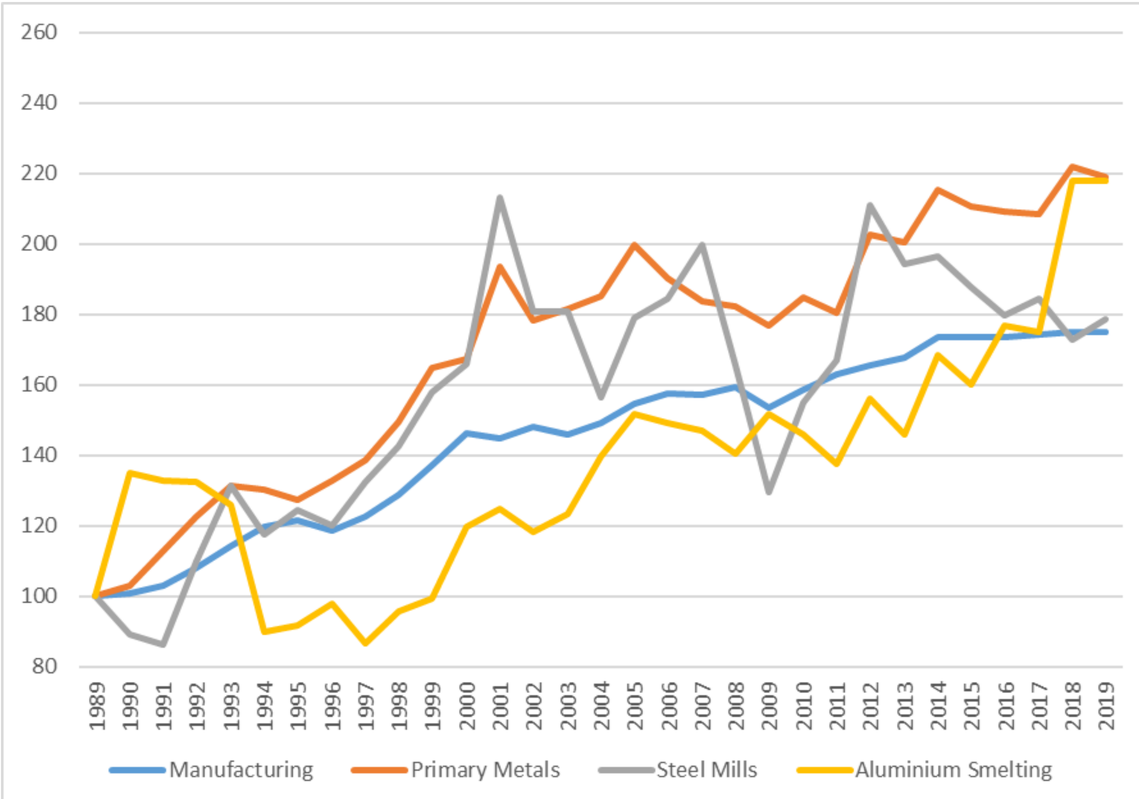
Sources: Statistics Canada Tables 36-10-0305-01; 36-10-0480-01.

Chart 5: Productivity (Output per Hour Worked) in Manufacturing, Transportation Equipment, Motor Vehicle Assembly and Aerospace 1989-2019 (1989=100)



Sources: Statistics Canada Tables 36-10-0305-01; 36-10-0480-01.

Chart 6: Productivity (Output per Hour) in Manufacturing, Primary Metals, Steel Mills and Aluminum Smelting 1989-2019 (1989=100)



Sources: Statistics Canada Tables 36-10-0305-01; 36-10-0480-01.

sured as output per hour, in the auto assembly sector has increased dramatically since 1989, to 113 per cent above its 1989 level. This contrasts with manufacturing as a whole, where productivity is 75 per cent above its 1989 level, and the transportation equipment sector, which is 95 per cent above. In contrast, aerospace is only 40 per cent above 1989 levels.

Turning to primary metals, Chart 6 shows the performance of productivity between 1989 and 2019.

Productivity in steel mills, while quite volatile, was 79 per cent above its 1989 level, similar to manufacturing overall, which was 75 per cent above 1989 level, but below the total primary metals sector, which was 119 per cent above 1989 levels. In contrast, the aluminum smelting subsector was 118 per cent above 1989 levels.

Thus both auto assembly and aluminum smelting had a strong productivity performance relative to total manufacturing.

Summary of Results

It is time to summarize our results. Table 2 below show the behaviour of each of our key variables of interest in 2019, relative to their levels in 1989.

Beginning with primary metals, we see that productivity grew significantly faster in aluminum smelting than in the primary metals sector as a whole as well as in aggregate manufacturing. This was driven entirely by stronger growth in output, as

Table 2: Output, Hours, and Productivity, (1989=100)

	GDP	Hours	GDP / Hour
Manufacturing	133.5	76.4	175.0
Transportation Equipment	166.4	84.4	195.4
Motor Vehicle Assembly	158.7	63.1	213.5
Aerospace	159.4	113.7	139.5
Primary Metals	131.3	59.1	219.0
Steel Mills	95.0	40.0	178.7
Aluminium Smelting	207.5	89.6	217.9

Sources: Statistics Canada Tables 36-10-0305-01; 36-10-0480-01; 36-10-0217-01

hours actually rose a little faster than in aggregate manufacturing and quite a lot faster than the primary metals sector as a whole. Steel mills had a very different performance. Here, productivity growth was similar to that in aggregate manufacturing, and lower than primary metals. Furthermore, the growth was only achieved because hours grew much more slowly: growth in output also lagged but not as much.

Thus the subsidies to the aluminum sector do look as if they have helped boost output growth, with hours growth also faster, at least compared to the rest of primary metals. However, investment subsidies to steel mills do not seem to have contributed to a stronger performance relative to other sectors—output, hours and productivity have all lagged.

Turning now to transportation equipment, we see from Table 2 that productivity growth in motor vehicle assembly was stronger than in transportation equipment as a whole. This was entirely driven by weaker hours growth; output growth was slightly slower. Productivity growth in motor vehicle assembly relative to aggregate manufacturing was driven both by slower hours growth and faster output growth.

For aerospace productivity growth lagged behind both transportation equipment and aggregate manufacturing. This weaker growth is largely (relative to transportation equipment) or entirely (relative to aggregate manufacturing) explained by much faster hours growth.

Conclusion

In this article we have looked at the four manufacturing industries that have been the principal focus of Canada's industrial policy between 1989 and 2019. For two of those industries—steel mills, aerospace—productivity growth has been comparatively weak. However, for aluminum smelting and motor vehicle assembly we did find comparatively faster productivity growth over the period studied.

Of course, we cannot make strong conclusions about the impact of industrial policy on productivity growth as we have not performed an econometric study that controls for the many other factors that could have affected, the performance of these sectors; it is entirely possible that without industrial policy performance would have been different.

Furthermore, we also have to consider the compositional effect of policy: to the extent that industrial policy keeps industries with an above average level of productivity viable, it keeps economy-wide productivity higher than if the industry were to disappear and workers move to sectors with lower productivity (or leave the labour force entirely). Without the support provided to the motor vehicle assembly industry during the great financial crisis, for example, there would almost certainly have been a significant shrinkage in this comparatively high productivity industry, especially given the support the U.S. provided to its auto sector during this period.

Whatever its impacts on productivity may have been, one thing we can say is that Canadian policymakers have not moved away from industrial policy. If anything, successive governments have increasingly embraced industrial policy as an essential part of their economic policy suite. One should be careful though to claim that productivity growth will benefit from industrial policy interventions.

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Climate Change and Productivity – An Exploration

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Abstract

This article explores the links between climate change and productivity. It finds that while much debate has focused on labour and multifactor productivity growth, improving productivity in the use of energy and materials is crucial to achieving net zero and requires much greater emphasis in productivity analysis. Although complementary productivity measures are available, these have not yet become mainstream. Productivity measurement also needs to be improved. Mainstream economic studies have long significantly underestimated the damaging impacts of climate change on growth and productivity. At the same time, studies today may overestimate the long-term costs of policies to address climate change.

Standard measures of productivity show few signs of a transition to more sustainable growth. Multi-factor productivity growth – the combined efficiency of factors inputs – has been falling at the global level, and the transition to net zero will likely require large investments in resource-intensive fixed capital, and not just intangible and human capital. While energy and materials productivity are improving, global material use continues to grow rapidly. Moreover, although CO2 emissions have decoupled from GDP growth in many advanced economies, the current pace of decoupling is far below what is needed for net zero.

The challenge for policy is how to design climate change policies to meet the global objective of net zero while limiting the impacts on productivity growth and living standards.

Climate change – the long-term change in the average and variability of weather patterns that define the Earth's climate – is already having negative impacts on economic performance, including on GDP, labour and multi-factor productivity (MFP). It is expected to have even greater impacts in the future, possibly threatening future living standards. Mainstream economic modelling studies have long suggested that the long-term impacts of climate change on growth and productivity

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would be relatively small, however (e.g. Tol, 2018; Nordhaus, 2019). Other studies question the findings and underlying assumptions of such modelling (Dietz and Stern, 2015; Stern *et al.* 2022; Stern and Stiglitz, 2023) and point to much larger, potentially devastating, impacts on growth and productivity (Dietz and Stern, 2015; Howard and Sterner, 2017), including impacts linked to the risk of the climate passing so-called "tipping points" (OECD, 2022). Recently, Kotz et al (2024) found that the world economy is already faced with a 19 per cent reduction of income within the next 26 years relative to a baseline of no climate change, independent of future emission choices. Bilal and Känzig (2024) find that a 1°C increase in global temperature leads to a 12 per cent decline in global GDP and that world GDP per capita would be 37 per cent higher today if no global warming had occurred between 1960 and 2019.

There are also considerable uncertainties about the impact of policies to address climate change on productivity. Many mainstream economic studies suggest that policies to address climate change could have a relatively high cost and a negative impact on growth and productivity, in particular in the context of scenarios aimed at limiting warming to 1.5°C (Dietz *et al.* 2021). Other studies find much smaller impacts of policy action, however, in particular in the long term (OECD, 2023; NGFS, 2023). Moreover, studies pointing to the high cost of policy action often do not consider the appropriate counterfactual, as they assume that climate change will have little impact on future GDP growth (Stern and Stiglitz, 2023). In addition, policies that encourage investments in innovation and technology to address climate change could support, rather than hold back, productivity and growth (Stern, 2022; Stern and Stiglitz, 2023).

The discussion on climate change and productivity is further complicated as labour and multi-factor productivity – the standard tools for productivity analysis – are not the only measures that are relevant to climate change. Other productivity measures, e.g. resource, energy and materials productivity, are not commonly discussed in the productivity and mainstream economics literature, although they are a key subject in environmental, resource and energy economics. Moreover, there are methodological challenges in measuring productivity in the context of the large environmental externalities linked to climate change. Another challenge is the absence of natural capital, as one of the "missing capitals" (Coyle, 2023), in most productivity analysis. Furthermore, the impacts of climate change go beyond those measured in GDP, requiring complementary analysis of well-being and other measures beyond GDP.

This article aims to disentangle some of the issues related to the impacts of climate change on productivity. It first provides a brief conceptualization of the different measures of productivity that are relevant to climate change and examines several economic measures of productivity, notably labour productivity and multi-factor productivity. It then examines various indicators linked to the physical processes linked to climate change, i.e. materials (or resource), energy and carbon emissions "productivity" (i.e. CO2 emissions relative to GDP). Next, it explores several indicators of environmentally-adjusted productivity, including the role of nature capital. All these sections present a range of evidence to illustrate various indicators and their relevance to the debate on climate change. It then explores how policies can best address climate change while also supporting productivity growth and standards of living. A final section summarizes and draws some conclusions.

Climate Change and Aggregate Productivity: Measurement and Evidence

Climate Change and Productivity Measurement

Exploring the links between climate change and productivity requires some elaboration of concepts and frameworks. After all, there are many possible measures of productivity and many potential links between climate change and productivity that can be distinguished. A first step in conceptualizing the relationship therefore lies in reviewing the main productivity measures that might potentially be affected by climate change. Table 1 draws on the OECD's Productivity Manual in showing the measures of labour, capital and multi-factor productivity that are commonly distinguished in productivity analysis (OECD, 2001). It includes an additional column on measures of materials and energy productivity, as climate change is closely associated with materials, resource and energy use, implying that relevant indicators of their productivity will be important to consider. It also emphasizes natural capital – defined as the living and non-living components of ecosystems that contribute to the provision of goods and services of value to people (Guerry et al. 2015) – as an additional capital input requiring attention in the context of climate-related productivity analysis. Following the OECD Manual, the table shows productivity measures for both gross output and value added, although much productivity analysis at the economy-wide level focuses on value added (and GDP), with the exception of KLEMS (Capital, Labour, Energy, Materials and Services) productivity analysis, that relies on gross output.

The measures in Table 1 all have their own relevance to climate change. Notably, and leaving the conceptual discussion of materials productivity for the next section (OECD, 2001):

- *Labour productivity and climate change.* Indicators of labour productivity relate a measure of output (gross output or value added) to a measure of labour input, typically employment or total hours worked. Measuring and understanding the relationship between climate change and labour productivity will provide an indication to which extent climate change is affecting economic performance at the firm, industry and economy-wide level and the ability of economies affected by climate change to generate growth in output and incomes.
- *Capital productivity and climate change.* Indicators of capital productivity relate a measure of output (gross output or value added) to a measure of capital (typically a measure of the services provided by a stock of capital). Changes in capital pro-

Table 1: Asset Types Included in the UK Volume Index of Capital Services

Type of Output Measure	Type of Input Measure				
	Labour	**Capital (including natural capital)**	**Materials or energy**	**Capital and labour**	**Capital, labour & intermediate inputs**
Gross Output	Labour productivity (based on gross output)	Capital productivity (based on gross output)	Materials or energy productivity (based on gross output)	Capital-labour MFP (based on gross output)	KLEMS multifactor productivity
Value Added	Labour productivity (based on value added)	Capital productivity (based on value added)	Materials or energy productivity (based on value added)	Capital-labour MFP (based on value added)	-
	Single factor productivity measures			**Multifactor productivity measures**	

Source: Modified from OECD (2001), Measuring Productivity - OECD Manual.

ductivity reflect the extent to which output growth can be achieved with lower welfare costs in the form of foregone consumption. Indicators of capital productivity can show how climate change is affecting – and possibly eroding – the capital stock and measure efficiency in the use of the capital stock. To be relevant to discussions on climate change, measures of the capital stock should include natural capital in addition to the standard measures of fixed and intangible capital. Some insights relevant to climate change might also be gained from the evolving composition of the capital stock, e.g. the growing importance of intangible assets such as R&D, software and data, that might signal a move towards a more knowledge-intensive and "weightless" economy involving less material use (Quah, 1999).

- *Multi-factor productivity (MFP) and climate change.* Indicators of MFP growth relate a measure of output (gross output or value added) to a measure of the combined input of labour and capital and – when related to gross output – also to intermediate inputs (energy, materials and services). Measures of MFP growth can help illustrate whether aggregate growth patterns are compatible with the transition to net zero and with sustainability more generally. More sustainable economic growth could imply growth that is for a large extent based on MFP growth, rather than on growth in factor inputs.

What Kind of Impacts Could Climate Change Have on Productivity?

Apart from considering the various indicators of productivity from a conceptual point of view, it may also be helpful to explore what kind of (direct) impacts climate change is likely to have on productivity and its various components, i.e. output, capital, labour input and intermediate inputs. For example, climate change is already having important impacts on agricultural yields that are expected to differ between different regions of the world

2 Although some of the impacts of climate change may be positive for specific regions and with small changes in temperature, the global impacts are expected to be strongly negative and highly damaging to the global economy.

(Pörtner *et al.* 2022).[2] Climate change will also have impacts on production in many other sectors directly influenced by weather conditions, e.g. tourism, fisheries and construction, or indirectly (e.g. insurance), and could affect many other sectors depending on its intensity.

Changing weather conditions could also affect labour input, for example as the intensity of work efforts will be affected by increasingly difficult working conditions due to extreme heat and due to growing migration from regions and countries that could become inhabitable. Impacts on the stock of fixed capital could include damages caused by extreme weather events, obsolescence of certain capital goods, or the impacts of increased weathering on the capital stock. Moreover, climate change could affect the costs and availability of intermediate inputs e.g. linked to the increased costs of cooling, lack of water, adaptation to climate change, insurance, etc. In principle, climate change might also affect technological change, e.g. in reducing investment in research and development (R&D) as firms and governments might focus more on the short term.

Finally, and potentially the most important, climate change is expected to have large impacts on the natural capital and ecosystems upon which the global economy is founded, with potentially disastrous consequences for many areas of economic activity, in particular when some of the planet's so-called "tipping points" would be exceeded.[3] As shown in the work of IPCC Working Group II, some of the impacts of climate change are already highly certain, while others are still somewhat uncertain (Pörtner *et al.* 2023).[4] What is clear is that they will all grow in magnitude with the extent of global warming. Tipping points, in particular, have long been ignored in the economics literature but are now regarded as possibly the most important and dangerous impacts of climate change, significantly increasing the magnitude of previously estimated economic impacts (OECD, 2022). Recent research suggests that some tipping points might be passed sooner than previously expected (Willcock *et al.* 2023).

These various direct impacts on outputs and inputs would affect productivity in specific firms and industries, and could lead to reallocation between firms and industries, with some firms and industries growing in size and others declining. Such reallocation might also occur across countries, with certain activities, such as agriculture or tourism, potentially relocating from countries heavily affected by climate change to others that are less affected. Climate change is also likely to have indirect impacts on productivity, linked to the policies implemented to address climate change. These will be discussed later in the article.

3 Tipping points include the disintegration of the Greenland ice sheet, the collapse of the West Antarctic ice sheet, the saturation of oceans as a carbon sink, the collapse of the Atlantic meridional overturning circulation (AMOC), and the dieback of the Amazon Forest as a carbon sink, among others (OECD, 2022).

4 Successive IPCC reports provide further detail on what the impacts of climate change might entail (IPCC, 2023).

The Macroeconomic Impacts of Climate Change on Growth and Productivity

What do we know about these direct impacts? Estimates of the future impacts of climate change on GDP and productivity, based on economic modelling, have been produced since the early 1980s and multiplied in the early to mid-1990s. Modelling studies typically focus on impacts on GDP instead of (labour) productivity, but often include assumptions about an exogenous pace of technological progress, that is driving MFP growth, and about capital deepening and labour input. However, with low and declining growth in labour input in many countries (Van Ark *et al.* 2023), impacts on long-term GDP growth are a close approximation of impacts on long-term labour productivity growth and thus instructive for this article.

Nordhaus (2019) notes that the available evidence suggests that the impacts of climate change will be nonlinear and cumulative, with relatively small impacts when climate change is limited and gradual, allowing economy and society to adjust, but that more extensive climate change can be highly disruptive to society and to natural systems. Tol (2018), in an overview of 27 studies from 1982 to 2013 finds small positive impacts of climate change on GDP with a modest degree (1°C) of global warming, to sizeable negative impacts with more extensive global warming. However, as noted by Tol (2018), there are considerable uncertainties with such estimates with a high change of negative surprises. Overall, he concludes that the impacts of climate change are considerable, but that "A century of climate change is likely to be no worse than losing a decade of economic growth." At the same time, the study points out the large differences between countries as regards the impacts of climate change, with the largest impacts expected in developing economies.

Howard and Sterner (2017) provide another meta-analysis and address a number of problems with previous studies, that they consider having created a significant downward bias in the literature. Their preferred estimate points to non-catastrophic damages of climate change on the level of GDP of between 7 and 8 per cent of GDP for a 3°C increase in global temperature, and between 9 and 10 per cent when factoring in catastrophic risks, considerably higher than the studies summarized by Tol (2018) and some three times higher than the average from previous studies.

Aligishiev *et al.* (2022) provide a recent overview of (some 40) studies on the macro-economic impacts of climate change. The estimates they report suggest relatively limited impacts of global warming on GDP, i.e. a median loss of only 1.5 per cent of annual global GDP in 2100 with respect to its reference level without climate change with global warming between 1.5° and 2.5°C, and a median loss of 3.3 per cent of annual global GDP in 2100 with global warming between 2.9° and 4.3°C.

They note, however, that "these studies may substantially underestimate the global cost of climate change in several ways and that global averages do not reveal the unequal distribution of climate change impacts". Specifically, they note that (Aligishiev *et al.* 2022): a) the estimates hide large negative effects in developing countries that are already hot or vulnerable; b) worst-case scenarios are typically missing, due to uncertainty in the literature; c) non-market impacts, e.g. biodiversity loss, are often imperfectly included as these estimates are uncertain and hard to quantify; d) the possibility of crossing societal tipping points (social conflicts, war, disruptive migration) is not considered as empirical data are lacking; e) GDP is at best a partial measure of welfare that does not consider distributional impacts.

The macroeconomic modelling studies of climate change briefly summarized above have increasingly been criticized over the past decade in being founded on a range of flawed assumptions (Dietz and Stern, 2015; Stern *et al.* 2022).[5] This includes problems with the integrated assessment (IA) modelling underpinning most of the studies, the lack of treatment of problems outside the scope of IA models, as well as some issues that could be addressed by IA models, but that have been ignored thus far and may lead to biased results. Moreover, the IA models have also been criticized in ignoring the possibility of large-scale events due to climate change, or "tipping points", and for their inability to connect sufficiently to physical science modelling of climate change (OECD, 2022). Aufhammer (2018) points to a number of key sectors for which a better understanding is required about their climate sensitivity and sets out key areas for further empirical research. Rising *et al.* (2022) also point to the many risks that are missing in the analysis of climate change, with a wide range of impacts understudied or challenging to quantify, and thus missing from the evaluations of climate risks.

Dietz and Stern (2015) show that the original IAM modelling, notably the so-called DICE (dynamic integrated climate-economy) model developed by Nordhaus (1992), has in-built assumptions related to the exogenous nature of economic growth, damage functions, and risk, that result in a large underassessment of the scale of economic damages linked to climate change. They modify these assumptions in three areas, i.e. a) by using a model of endogenous growth, where climate change affects long-term growth, not just current output; b) by using a different damage function where damage can increase rapidly if temperatures rise; c) by using different assumptions as regards the risks associated with climate change. The resulting analysis with the DICE model shows much larger impacts of climate change on economic growth in the long run than the standard analysis with the DICE model.

Stern and Stiglitz (2023) also point to a number of analytical flaws in standard macroeconomic studies of climate change. First, they note that many studies get the counterfactual wrong by underestimating the growing scale of damages resulting from climate change. Second, they note that most studies are underestimating the risks of climate change, and do not account for the systemic nature of that risk. Third, they note that the standard argument over-

5 Modelling is not the only way to estimate the impacts of climate change. Several studies have estimated the impacts of climate change using weather observations. See Pilat (2024) for some further discussion.

looks many other market failures that reduce efficiency, and affect investment, innovation and growth. Fourth, they note that markets discount the future at too high a rate, leading to short-termism and under-investment in the future, e.g. in R&D. Finally, they suggest that the standard models ignore distributional effects, notably in giving little weight to future generations, but also to poor people and poor countries, instead emphasizing efficiency.[6]

Economic analysis that incorporates the risk of one or more tipping points in the economic costs of climate change find significantly higher costs and impacts on GDP (Dietz *et al.* 2021), often with magnitudes several times higher than mainstream models. Dietz et al (2021) note that their estimates are probably underestimates, as some tipping points, their interactions and impact channels, have not yet been adequately covered in the literature. Stern and Stiglitz (2023) note that assuming that current growth rates can be sustained without stronger climate action is a misleading counterfactual. Overall, it appears therefore that macroeconomic studies have significantly underestimated the impacts of climate change on growth and productivity.

Most of the estimates on the economic impacts of climate change focus on standard measures of GDP and productivity growth, which implies they do not account for environmental externalities and the increase in "bad" outputs that would accompany climate change. The fourth section of this article will discuss some studies that adjust for these externalities.

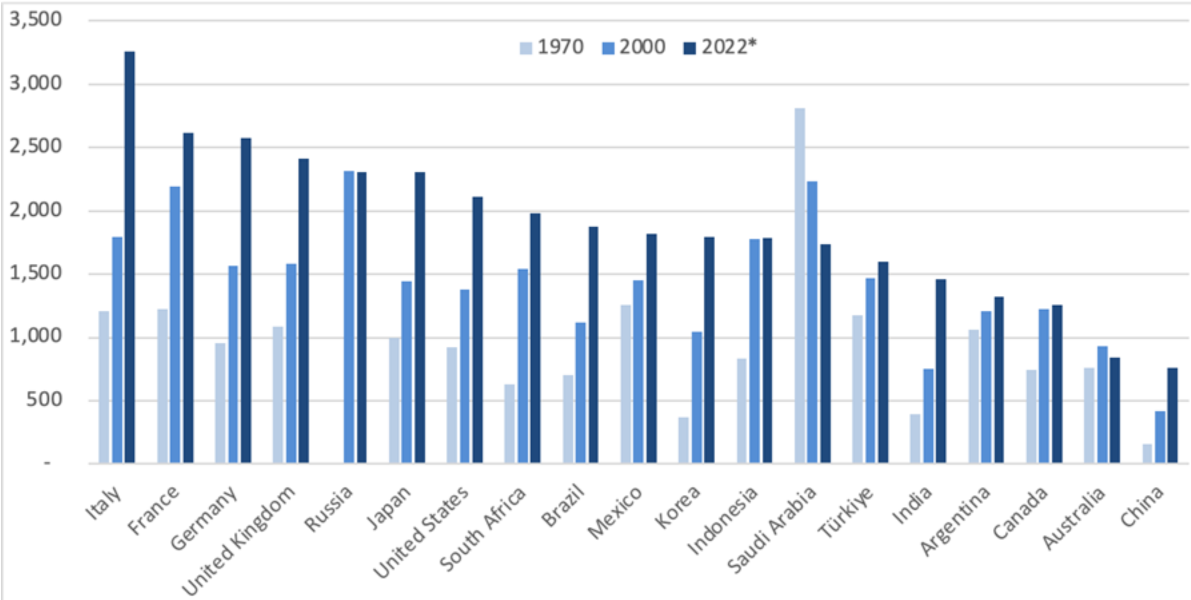
Resource Productivity

Measures of resource productivity are particularly important for the analysis of climate change. They typically measure the efficiency of resource use, e.g. of energy or materials, but can also be used to measure the CO2 or greenhouse gas (GHG) emissions that accompany that resource use. The mainstream productivity literature generally does not devote much attention to resource productivity, as it is not considered central to the analysis of economic and productivity performance at the firm, industry or economy-wide level. However, these indicators are extensively used in environmental policy and energy policy analysis and have a good foundation in methodology and data.

Addressing climate change will require large improvements in the efficiency of resource use, notably in the use of materials contributing to GHG emissions, i.e. fossil fuels, as well as certain materials contributing to such emissions linked to agriculture, industry and construction (OECD, 2019). Moreover, increasing resource productivity is important as growing materials use is accompanied by a range of negative side effects on the environment, such as loss of biodiversity (OECD, 2019). This section explores some of the key indicators and ev-

6 The large macroeconomic impacts of climate change are accompanied by large variations across countries, regions, sectors, firms and social groups. For space reasons, this article will not review the extensive sectoral literature on climate change, nor the country-specific and regional impacts. See Pilat (2024) for some references.

Chart 1: Materials Productivity in G20 Countries, 1970, 2000, and 2022 (GDP relative to material footprint, in USD per tonne, 2015 PPPs)



Note: * 2019 for EU countries and Türkiye, 2022 for all other countries.
Source: OECD, Material Flow Accounts, OECD Data Explorer, accessed 6 June 2024.

idence.

Measuring Materials Productivity

Conceptually, measures of materials productivity relate gross output, GDP or value added to the total volume of materials used to produce that output. For example, OECD measures of materials include the volume of biomass (mainly linked to agriculture and forestry), fossil fuels, metals and non-metallic minerals (with the bulk linked to the construction sector) used in the production process (OECD, 2019). Materials productivity is then defined as the monetary value (in terms of real GDP) generated per unit (tonne) of materials used (OECD, 2017). This measure is often expressed in terms of domestic material consumption (DMC), which is calculated as the domestic extraction used minus exports plus imports and expressed in terms of weight (OECD, 2017). However, indicators based on DMC do not include the indirect material flows associated with internationally traded products, and countries might improve their materials productivity by drawing more on material flows embodied in imported goods.

Productivity measures based on the so-called material footprint of an economy adjust for these international flows and are shown in Chart 1.[7] It shows large differences between countries in 2022, with a range from around 750 USD of value added per tonne of materials in China, to over 3200 USD per tonne in Italy. These

7 Material footprint represents the portion of raw materials extracted anywhere in the world that are needed to satisfy final demand of an economy. It includes materials that are directly used by an economy in the form of raw materials, semi-processed materials or processed goods, and materials that are associated with the production of imported goods but not physically imported. See OECD (2020).

differences partly reflect structural factors, such as the relative importance of extractive sectors such as mining (e.g. in Australia and Canada); the level of economic development, including the importance of the construction sector; the dependency of a country on fossil fuels; the relative importance of agriculture and forestry, etc. Despite these structural differences, the cross-country differences also point to further scope for productivity growth. Between 2000 and 2022, some countries (e.g. China, India, Italy and Korea) significantly improved materials productivity. Others (e.g. Australia, Indonesia, Russia and Saudi Arabia), however, experienced stagnant of negative productivity growth.

A global study of materials and resource productivity for the period from 1970 to 2010 (Schandl *et al.* 2017) shows an increase in materials use (excluding fossil fuels) from 22 billion tonnes in 1970 to 70 billion tonnes in 2010, and a rapid acceleration in material extraction since 2000. It finds that materials productivity globally has declined since 2000, due to a shift in production from materially-efficient economies, e.g. Japan, Korea and many European countries to less efficient ones, e.g. China, India and Southeast Asia.

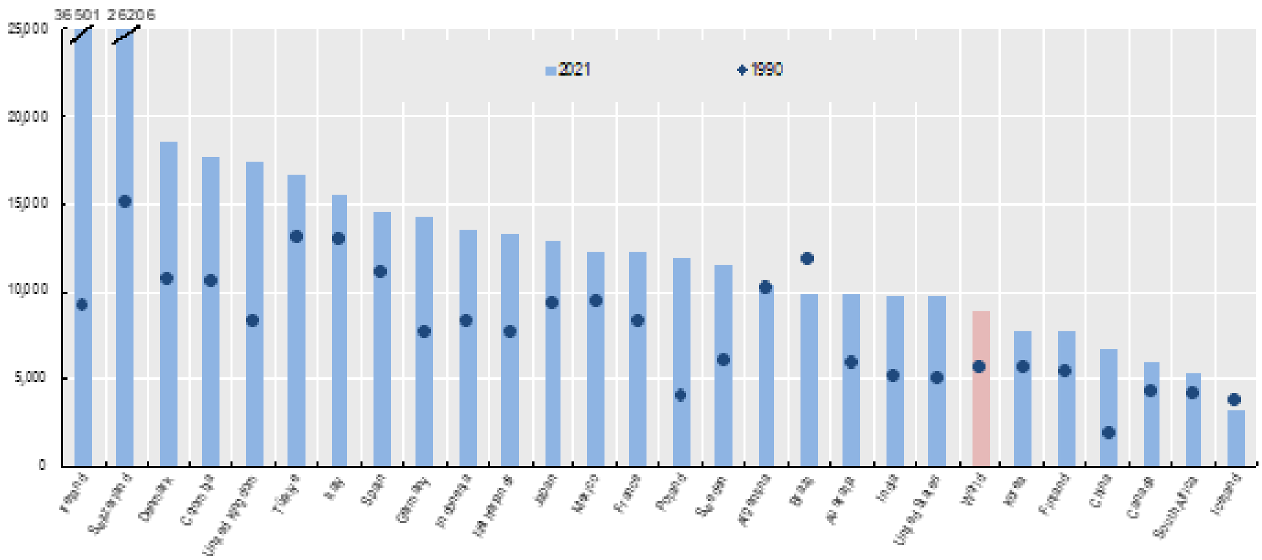
Understanding the factors that influence materials and resource productivity over time can help devise strategies to reduce their use and improve productivity. Gan *et al.* (2013) examine a range of factors that influence resource productivity across countries. They point to a few stylized facts, notably that: 1) resource productivity increases with income; 2) countries with high population density tend to have higher resource productivity; 3) the process of economic development and changing economic structures affect resource productivity; 4) raw material exports tend have a negative impact on resource productivity, as a strong focus on exporting may reduce pressures to improve efficiency in resource use.

Studies are now emerging on the potential of improvements in materials productivity for addressing climate change. Scott *et al.* (2019) examined the contribution of improvements in materials productivity for the UK emissions gap. They estimated that a range of policies could improve materials productivity. This includes policies focused on the redesign of products, so they would use less carbon-intensive products, or on reducing the demand for new products and extending the life-cycle of products. In another study, Flachenecker and Kornejew (2019) find that firms' improvements in material productivity reduce the CO2 footprint of firms. Moreover, improvements in material productivity had a positive and causal impact on the microeconomic competitiveness of firms.

Haas *et al.* (2015) suggest that improved circularity – and thus improved materials productivity – will require a shift to renewable energy, a reduction in the growth of societal stocks, and a significant increase in circularity of all products. OECD (2023b) emphasizes that rising global material extraction means that most materials are either wasted, lost or remain unavailable for reuse as they are locked in long-lasting stocks such as buildings. It also notes that reaching net zero will require the development of a more circular economy and a reduced material footprint.

The likely impacts of policy actions to

Chart 2: Energy Productivity, selected OECD and G20 countries, 1990 and 2021 (USD per tonne of oil equivalent, 2015 PPPs)



Source: OECD, Green Growth Database, accessed on 28 March 2023.

move to net zero on materials productivity are uncertain and may be limited. Studies have shown that the volume of resource extraction (including metals) needed for the transition to renewable sources of energy is many orders of magnitude smaller than the current volume of resource extraction associated with fossil fuels (Nijnens *et al.* 2023). Some materials, notably fossil fuels, should be phased out to achieve net zero, boosting overall materials productivity, but the scope and importance of productivity improvements in the use of other materials is less certain. The transition to net zero and move to renewable energy is expected to lead to greater demand for metals, in particular. Metals extraction and use have a wide range of environmental consequences, including toxic effects on humans and ecosystems (OECD, 2019). On the other hand, metals are more easily recycled than many other materials. Other materials also have a wide range of environmental impacts, not all related to climate change, but on areas such as biodiversity (e.g. due to changing land use or the extraction of construction materials). Improving materials productivity is therefore not only important for climate change, but also for the state of the environment more generally.

Energy Productivity

Another measure of productivity relevant to climate change is the productivity of energy use, i.e. the output generated (typically in terms of real GDP) per unit of total primary energy supply (TPES), where energy supply is typically expressed in tonnes of oil equivalent (OECD, 2017). Energy use will have different impacts on climate change depending on the sources of energy, e.g. fossil fuels versus renewable sources, but climate change is also affected by the efficiency of energy use, notably the use of energy-efficient technologies and processes, as well as the degree of electrification. Available indicators of energy productivity (Chart 2) show large differences between leading countries such as Ireland,[8] Switzerland and Denmark, and countries with low levels of energy productivity such as China, Canada and South Africa.

The OECD's data suggest that global energy productivity rose by over 50 per cent between 1990 and 2021 (i.e. an annual average growth rate of just over 1.3 per cent), with particularly high productivity growth in several central European countries (e.g. Poland), as well as in China and Ireland. Brazil and Iceland experienced negative growth in energy productivity over the period, however, and Argentina's energy productivity grew by only 2.5 per cent. The cross-country differences suggest scope for improvement, with potential benefits for climate change. Chart 2 suggests that countries with very low levels of energy productivity have not experienced faster productivity growth than those with high levels of energy productivity, however.

Du and Lin (2017) estimated a more complex measure of total-factor productivity energy change for 123 economies worldwide. They find an increase in energy productivity globally of almost 35 per cent between 1990 and 2010, mainly driven by technological progress, with higher energy productivity growth in the more developed economies and no evidence of convergence in energy productivity between developed and developing economies. In a study for a more limited number of advanced economies, Apergis and Christou (2016) also find no evidence of full convergence but point to the presence of some convergence "clubs". They do, however, suggest that energy productivity across countries will converge in the long run. Atalla and Bean (2017), in a study of energy productivity for 39 countries over the period 1995-2009 find that improvements in sectoral energy productivity were the main driver behind aggregate improvements in energy productivity, with a more limited role for structural shifts, e.g. from industry to services. They also found that higher income levels and higher energy prices were associated with greater energy productivity.

Energy productivity is linked to CO2 emissions and climate change through the emissions intensity of energy. In principle, countries could move from fossil fuels to clean sources of energy without improving in energy productivity. Measures of energy productivity will therefore not necessarily move at the same speed (or even always in the same direction) as measures of carbon emissions productivity (OECD, 2017), discussed below. For example, Iceland has a very low level of energy productivity, but low levels of carbon emissions, linked, amongst others, to its high use of renewable energy, notable geothermal energy.

The future evolution of energy productivity is uncertain and could move in different directions. Improvements in energy efficiency and efficiencies linked to electrification could improve productivity. How-

8 Ireland's GDP figures are affected by the large role of multinational firms in the country, which tend to inflate GDP and will therefore also considerably inflate its level of energy productivity.

ever, the transition to abundant and possibly very cheap renewable energy could also contribute to increased demand for energy through the so-called "rebound" effect, with improvements in energy efficiency leading to an increase in energy consumption (Dimitropoulos, 2007), with potential impacts for climate change. For example, in the transport sector, growing energy efficiency is counteracted by growing demand for larger cars, notably SUVs (Brugger *et al.* 2021). At the same time, new societal trends, such as the sharing economy, might help reduce energy demand (Brugger *et al.* 2021).

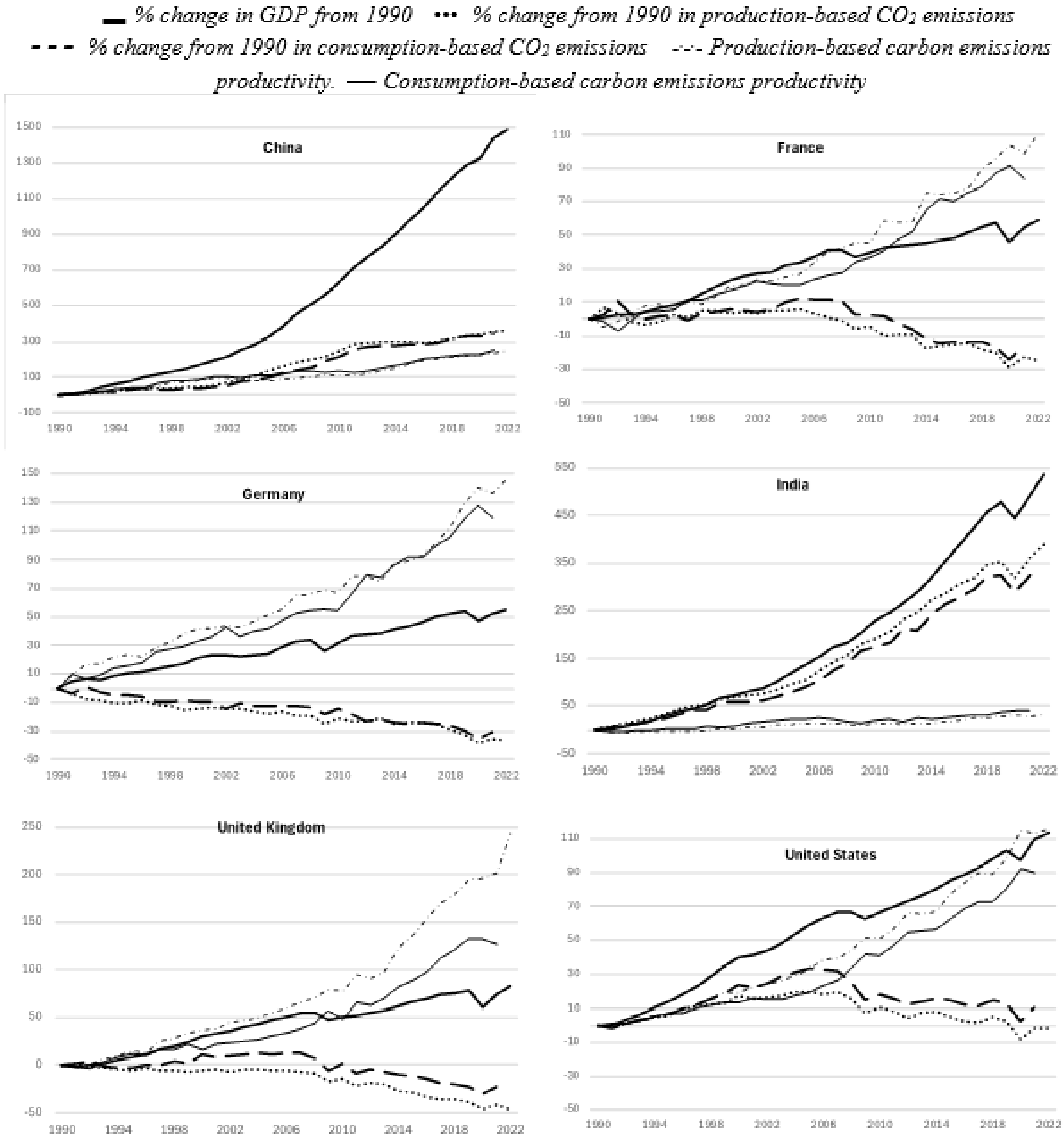
The "Productivity" of Carbon Emissions

Although carbon emissions are a byproduct of resource use and not a typical material or resource, like raw materials or energy, "productivity" indicators related to carbon emissions are the most closely associated with climate change of the three types of indicators discussed in this section. They can be derived in several ways and reflect either emissions linked to domestic production of CO2 or to the CO2 emissions linked to satisfying domestic demand, thus adjusting for emissions generated abroad to satisfy domestic consumption (OECD, 2017). Chart 3 shows these two key indicators of carbon emissions productivity levels for six key G20 countries for the period 1990-2022.

The graphs illustrate several features of carbon emissions productivity. First, as with other indicators of materials and resource productivity, there has been considerable improvement in carbon productivity in several countries over the past decades. Most advanced countries have experienced a relative decoupling between GDP growth and emissions, with GDP growing faster than emissions (OECD, 2017; Pilat, 2024). Some – e.g. France, Germany and the United Kingdom in Chart 3 – even experienced an absolute decoupling of GDP growth and emissions, with GDP growing and emissions falling (OECD, 2017; Pilat, 2024). Analysis by the IEA attributes most of the decoupling to four factors; a) rapid growth in clean energy investment; b) growing electrification; c) improvements in energy efficiency; d) a transition away from coal (Singh, 2024). In China and India, GDP growth and CO2 emissions have not decoupled yet, however, and emissions have been rising, in particular in China.

Second, there are considerable differences between the production-based and consumption-based indicators of carbon productivity. The production-based indicators cover CO2 produced in a country without accounting for trade flows, whereas the consumption-based perspective considers emissions from the perspective of final demand, including trade flows (OECD, 2017; Yamano and Guilhoto, 2020). Countries may be able to reduce their emissions from a production perspective by shifting polluting industries abroad or by importing carbon intensive products from abroad. Increasing demand-based carbon productivity is therefore more difficult than increasing production-based carbon productivity and far fewer countries were able to achieve an absolute decoupling between GDP growth and growth in carbon emissions on the demand side than on the production side (OECD, 2017). Moreover, the

Chart 3: The Relationship Between GDP and CO2 Emissions and Carbon Emissions Productivity, Selected G20 Countries, 1990-2022



Source: Our World in Data (2024), https://ourworldindata.org/co2-and-greenhouse-gas-emissions, drawing on World Bank and Global Carbon Budget.

rate of decoupling is considerably lower on the demand-side than on the production side (Pilat, 2024).

The available data also point to large cross-country differences in carbon emissions productivity, linked to the carbon intensity of different economies and their respective use of fossil fuels. China, as several other BRIICS economies, i.e. India, Russia and Saudi Arabia, have particularly low levels of carbon emissions productivity, together with some OECD countries, such as the United States, but also Australia, Canada, Korea and Poland (Pilat, 2024). Countries in Western Europe, e.g. France, and South America tend to have the highest levels of carbon emissions productivity. In principle, these large differences could point to scope for productivity growth. However, there is no evidence that countries with low levels of carbon emissions productivity have experienced more rapid growth in carbon emissions productivity than those with high levels (Pilat, 2024).

Achieving zero global emissions of CO2 (or of all greenhouse gases - GHGs) by 2050 would require a rapid acceleration in carbon emissions productivity growth. The two countries with the highest level of production-based carbon emissions productivity in the OECD – Switzerland and Sweden – had a corresponding low carbon intensity of some 60 grammes of CO2 for every USD of GDP in 2021 (Pilat, 2024) and had experienced an annual average decline in carbon intensity over the previous 30 years of around 2-3 per cent. Bringing emissions down to 10 grammes of CO2 for every USD of GDP in 2050, i.e. close to zero grammes, would require doubling that rate of decline to about 6 per cent annually. For the OECD as a whole, with production-based carbon emissions intensity in 2021 at only 180 grammes of CO2 for every USD of GDP, the annual average average rate of decline in carbon intensity would need to increase from just over 2 per cent from 1990 to 2021, to 9.5 per cent from 2021 to 2050 to achieve 10 grammes of CO2. The current pace of decoupling is thus far below what is needed.

Resource and Materials Productivity in a KLEMS Framework

The indicators in this section presented thus far all relate measures of material use to GDP. However, measures of resource, materials and energy productivity can also be derived in a KLEMS accounting framework, thus relating material use to gross output. For example, Inklaar and Timmer (2007) provide evidence on relative levels of output, inputs (including energy, materials and services) and productivity at the industry level for seven countries. They derive comparisons of output and input levels by deflating data from input-output tables by a set of relative prices developed for industry-level productivity comparisons. The article finds that European countries use much less energy in production than the United States, and that Canadian production is the most energy intensive. On the other hand, the United States (and Canada to a lesser extent) uses far fewer materials in production than European countries.

Mulder and Groot (2012) use the EU-KLEMS database (O'Mahony and Timmer, 2009) combined with IEA data on physical energy to explore the development of energy intensity across 18 OECD countries and 50 sectors over the period 1970-2005. They find declining levels of energy intensity – i.e. improvements in energy productivity – in most manufacturing sectors, but a much slower decline in services sectors, with greater variation across subsectors. They also find that changes in the sectoral composition of economies explain a considerable and growing part of the changes in aggregate energy intensity.

Productivity Measures Adjusted for the Environment

The measures set out in the previous two sections can provide a first step in measuring the links between climate change and productivity. Another step involves adjusting the measures of output and factor inputs in Table 1 for environmental externalities (negative and positive) and by explicitly including natural capital in aggregate capital input. As greenhouse gas emissions and other forms of pollution are not priced by the market, the costs and damages linked to such pollution are not reflected in the output and input measures that are used for productivity measurement. The standard productivity measures shown in Table 1 will therefore provide a biased perspective of productivity growth (Pittman, 1993). Moreover, including natural capital in total capital input will help demonstrate its contribution to economic growth and productivity and can also help indicate how such capital is evolving as a result of resource extraction and exploitation. Potentially, there are several such measures that could be developed. Not all potential measures are equally important or meaningful, however, and Table 2 shows some of the most prevalent measures in the literature.

Adjusting for Bad Outputs

A first measure (No. 1) involves *adjusting output and productivity measures for the environmental damages (outputs) created by by-products of the production process*, e.g. carbon or other greenhouse gas emissions, or other pollutants affecting the environment and human health (Brandt *et al.* 2017). As noted by Agarwala and Martin (2022), "one problem is that the standard approach to measuring productivity adopts a private goods perspective, permitting by assumption the 'free disposal' of bad outputs." Not including these negative environmental externalities in the calculation of GDP and productivity may lead to an overly positive assessment of productivity for countries that use heavily polluting technologies in the production process. On the other hand, GDP and productivity may be underestimated in countries that invest in cleaner production processes, as these investments may not directly increase GDP but will help to reduce the negative externalities linked to pollution.

Cárdenas Rodríguez *et al.* (2023) estimated this adjustment for the period 1996-2018 for all OECD and G20 economies, with pollution being represented by greenhouse gases such as CO2 and nitrous oxide, and several other air pollutants. They found positive (though often small) adjustments to GDP growth in 33 countries, with particularly high adjustments in France, Germany, Italy, the United Kingdom and

Table 2: Selected Environmentally Adjusted Productivity Measures

Measures	Definition	Adjustments
A. Adjustments to output – environmental externalities		
1. Labour productivity adjusted for bad outputs	Output adjusted for bad outputs / Hours worked	The value of bad outputs (e.g., GHG emissions or air pollution) is deducted from output
2. Labour productivity adjusted for unmeasured environmental protection output	Output adjusted for unmeasured environmental protection output / Hours worked	The value of unmeasured environmental protection is added to output
B. Adjustments to capital input – natural capital		
3. Multifactor productivity measures adjusted for investment in selected natural capital assets measured at private costs	Output / Factor inputs (including selected natural capital assets valued at private costs)	The services of natural capital, valued at private costs, are added as a capital input

Source: Modified from Agarwala and Martin (2022).

Sweden, reflecting the effect of pollution abatement in these countries. They also found and negative adjustments in 19 countries, with particularly high adjustments in Brazil, China, Korea, India, Indonesia and Turkey, reflecting the pollution-intensive nature of growth in these countries.

Hua and Wang (2023) also provide estimates of environmentally adjusted MFP growth (EAMFP) for 51 OECD and G20 countries over the period from 1990 to 2020 that includes natural capital and bad outputs. They find that EAMFP growth is below MFP growth in 40 out of 51 countries, i.e. with bad outputs having a negative impact on MFP growth. They note that the gap between MFP and EAMFP growth is largest in lower-middle income economies, such as India and Indonesia, where growth was accompanied by high emissions of pollutants.

Some studies have criticized EAMFP measures. For example, Guarini (2023) suggests that the underlying assumptions of constant returns to scale, perfect competition and perfect input substitutability are unrealistic in the context of environmental policy and innovation.

Adjusting for Good Outputs

A second potential measure involves *adjusting GDP and productivity measures for unmeasured environmental protection output*. This involves an adjustment for an environmental "good" rather than an environmental "bad". For example, EU data shows that, in 2020, expenditure on environmental protection and resource management activities accounted for 2.5 per cent of total EU gross value added (Eurostat, 2022). However, much of such expenditure is currently considered as intermediate consumption and thus not included in GDP (UN, 2014). A case can be made for its inclusion, however (Agarwala and Martin, 2022).

Agarwala and Martin (2022) argue that the available data may still underestimate total expenditure on environmental protection. They note that in the United Kingdom, available statistics underestimate the overall output of all firms in the economy on environmental protection activities, as they only cover the four industries most likely to engage in environmental protection (mining, manufacturing, energy and water supply). Moreover, the recorded output may also be underestimated, as much of firms' expenditure is own-account (and therefore not recorded in GDP) and non-market (as firms incur costs that are not included in output or prices). Estimating these expenditures and including them in GDP as an "environmental good" will tend to increase the level of GDP and thus change the rate of labour productivity growth.

Agarwala and Martin (2022) measure the time spent on "green tasks", using detailed occupation data and a list of occupation-specific tasks, including "green tasks" and apply this to measure total output of environmental protection activities in the United Kingdom. As a result of their approach, that included various adjustment to avoid double counting, they find that unmeasured environmental protection would add some 6-7 per cent to the level of UK GDP. Moreover, as a result of the adjustment, they also find that UK labour productivity grew slightly faster between 1997 and 2019 than with standard productivity measurements. Making such adjustments for a wider set of countries would be valuable in establishing a broader understanding of the likely size of such investments.

Natural Capital as a Capital Input

A third approach to adjusting standard productivity measures for the environment involves *including natural capital in the measure of capital stock* that is used for productivity analysis (Brandt *et al.* 2017; Cárdenas Rodríguez *et al.* 2023). Standard productivity measures typically include labour input and measures of (produced) fixed and intangible capital, but do not include natural capital, such as sub-soil assets and other productive capital, as well as non-agricultural land, forests and protected areas, even though the use and extraction of such assets may contribute to GDP. Including natural capital as an asset will have an impact on measured productivity growth and demonstrate the contribution of natural capital to GDP growth.[9]

Recently, Cárdenas Rodríguez *et al.* (2023) estimated the contribution of a range of natural capital assets to GDP growth over the period 1996-2018 and found sizeable positive effects for Saudi Arabia, Russia, Australia, Chile, China and Brazil. However, even in these countries, natural capital accounted for less than 10 per cent of output growth. Denmark, Mexico, Norway and the United Kingdom were among the countries with a negative contribution of natural capital to output growth, implying that they relied less on the extraction of natural capital (e.g. oil in the case of Norway) than before (Cárdenas Rodríguez *et al.* 2023).

The work by Brandt *et al.* (2017) and Cárdenas Rodríguez *et al.* (2023) focuses on a subset of natural capital assets and

9 Including natural resources – or natural capital – also helps in explaining productivity differences across countries. Freeman et al. (2021) show that including natural resources in cross-country productivity comparisons explains most of the productivity advantage of resource-intensive countries such as Qatar and Saudi Arabia.

10 A variant of this approach, better suited to cross-country comparisons, involves the use of producer reservation prices, where natural resources are valued by world-market resource prices (Freeman *et al.* 2022).

uses *private user costs* to value natural capital, as is the standard approach for productivity measurement (OECD, 2001).[10] To inform analysis of the link between climate change and productivity, this has some limitations. First, this measure of natural capital excludes several key assets, such as soil and freshwater resources, oceans, and biodiversity. that provide important ecosystem services. Second, measuring the services of these assets by private costs will not necessarily reflect their social costs, which are likely to be much higher than the private costs, e.g. due to the impacts of resource extraction and the use of natural capital on biodiversity and the environmental ecosystem. The use of private user costs does not provide a measure of welfare and does not address the negative environmental externalities linked to the extraction of natural capital.

Going beyond such measures is challenging, however. A first challenge is to expand the range of natural capital assets beyond sub-soil assets for which market prices are available, and include assets such as land, but also aquatic and freshwater resources. Some of these are treated as non-produced assets in the national accounts, with no investment going into their creation (Martin and Riley, 2023). The measurement of these assets raises several problems, which is why little progress has been made in incorporating them into productivity analysis. A second challenge is their valuation, which should reflect the net present value of future benefits flowing to the natural capital over its lifetime (Martin and Riley, 2023). A question here is whether those benefits should include environmental and social benefits of natural capital, and how these can be valued. Few studies are available at this stage that apply this broader approach to natural capital to productivity measurement.

An empirical application that starts to go into this direction is the work by Managi and Kumar (2018) and Kurniawan and Managi (2019), who measured what they called "inclusive wealth" over the period 1990 to 2014 for 140 countries. These studies defined inclusive wealth as the combination of human, produced and natural capital, with accounting prices measuring the social value of goods and services rather than private user costs. Drawing on this work on inclusive wealth, Managi and Kumar (2018) and Dasgupta *et al.* (2022) show that globally, the per capita stock of produced capital doubled between 1990 and 2014, whereas the per capita stock of human capital increased by some 13 per cent and the value of the per capital stock of natural capital declined by 40 per cent.

Sato *et al.* (2018) estimated TFP growth for 43 countries, both based on the concept of inclusive wealth (and thus including natural capital) and unadjusted for natural capital, as a way of assessing the sustainability of growth in different countries. The study found significant differences in the respective TFP growth rates for certain countries, with some – such as Australia, Canada, China, Japan, Mexico, the United Kingdom and the United States having significantly higher TFP growth when adjusted for natural capital. On the other hand, several other countries had significantly lower – and often negative – TFP growth rates when adjusted for natural capital, including Bolivia, India, Kenya, Senegal and Turkey.. This suggests that natural capital grew faster than other capital inputs in these countries, potentially reflecting high rates of depletion. Jumbri and Managi (2019) used a similar approach, covering 140 countries and find similar results, with significant differences between TFP measures based on inclusive wealth – i.e. including natural capital – and those not based on that concept.

These studies, and others like it, demonstrate the relevance of measures of natural capital to work on productivity. Drawing on natural capital in the process of economic development is not necessarily a problem, as long as the natural capital is converted into other capital, i.e. fixed, intangible or human capital. Van Krevel (2021) finds that many countries were able to turn their depleted natural capital into produced (i.e. fixed or intangible) and human capital, thus supporting economic development.

Such studies cannot assess whether the rate of resource depletion is ecologically sustainable, however, and whether the deprecation of natural capital may promote economic wealth at the cost of ecological health (Van Krevel, 2021). Scenario studies suggest that development paths that combine income growth with a much-reduced reliance on natural resources provide the most sustainable way towards increasing inclusive wealth and also to mitigating and adapting to climate change (Kurniawan and Managi, 2021).

While the potential productivity measures discussed in this section provide important extensions beyond the standard measures discussed in the previous section, there is a question whether they go far enough, and whether GDP – even when adjusted for environmental externalities - is sufficient to capture the range of economic and social impacts of climate change, including impacts on well-being. As noted by Stern and Stiglitz (2023), GDP is not a good measure of well-being, in particular in the context of climate change. They note that what is relevant is not growth in GDP, but growth in a multidimensional measure of well-being, e.g. as suggested by Stiglitz *et al.* (2009). As this article is mainly focused on productivity, it will not explore the link between climate change and well-being any further.

Addressing Climate Change While Supporting Productivity and Well-being

The Impacts of Climate Change Policies on Productivity

The article has thus far mainly explored the direct impacts of climate change on productivity. A second set of impacts linked to climate change are indirect as they result from the policies and actions aimed at reducing the direct impacts of climate change. These actions will have their own – positive and negative – impacts on productivity and economic performance. However, these impacts should be considered in the context of the large social and economic costs that would occur if action were not taken and climate change would be allowed to run its course without restraint (Stern and Stiglitz, 2023).

Several impacts of climate-related policies on productivity can be distinguished (e.g. Kozluk and Zipperer, 2015; Stern and

Stiglitz, 2023), notably:

- *Impacts on productivity and factor inputs linked to the costs of regulation and environmental policies aimed at addressing climate change.* Many studies of environmental policy suggest that policies and regulations to improve the environment (and address climate change) are a cost and burden to firms, distorting markets and diverting resources from more productive uses, thus reducing productivity.
- *Impacts on productivity linked to policy-induced innovation and technological change.* The so-called "Porter Hypothesis" argues that well-designed environmental policies and regulations will encourage firms to innovate, which could help increase productivity (Porter, 1991). The hypothesis involves several variants (Kozluk and Zipperer, 2015), with the "weak" one suggesting that more environmental regulation will encourage more environmental innovation; the "strong" one suggesting that environmental policies can improve firm's overall competitiveness; and a "narrow" one suggesting that only certain types of environmental regulation will increase innovation and firm performance.
- *Impacts on productivity linked to policy-induced shifts in trade and competitiveness.* When countries take unilateral climate policy action in a globalized economy, firms might move their activities to countries with fewer environmental restrictions, leading to "pollution havens". Such relocation could have impacts on productivity in the countries affected (Aldy and Pizer, 2015). Trade policy actions to limit the reallocation of production, e.g. by taxing imports of carbon-intensive products, might also influence productivity and competitiveness. On the other hand, in line with the Porter hypothesis, countries addressing environmental challenges earlier might benefit from first-mover advantages that could allow them to benefit from markets for low-carbon products abroad.
- *Impacts on productivity linked to policy-induced structural change and reallocation.* Policies to address climate change are likely to have impacts within and across sectors of the economy, with some firms and sectors gaining from growing demand for low-carbon products and technologies, and others faced with declining demand. Moreover, firms successfully engaged in low-carbon innovation may gain market share over firms that are not able to adjust to changing conditions. This will lead to reallocation across the economy, both within and across firms and sectors, with uncertain impacts on aggregate productivity.
- *Impacts on productivity linked to policy-induced shifts in demand.* Policies for net zero may also have impacts on aggregate demand, e.g. linked to changing consumption patterns and new social norms (Stern and Stiglitz, 2023). These could lead to new opportunities and markets and also affect productivity, e.g. through new areas of innovation to meet emerging demand, and through changes in the localization of production or shifts between and within industries (e.g. from individual to public transport).

The measures of productivity shown in Table 1 will be affected in different ways by the direct impacts and indirect impacts of climate change. The aggregate effect of these various impacts is uncertain, although studies have explored some of its dimensions at different levels of analysis (i.e.

firm, industry or economy-wide). The various impacts are related and will interact, and empirical studies will not always be able to distinguish them very clearly, if at all.

Some of the likely impacts of policy action, such as costs linked to taxation and regulation, are widely expected to be negative, whereas others, such as impacts linked to innovation and technological change, may well be positive. Stern and Stiglitz (2023) point to several factors that may help strengthen productivity in response to climate policies, including improved resource efficiency; increasing returns to scale; stronger "system" productivity, e.g. in energy and transport systems as well as in cities; a faster move to the knowledge frontier due to increased social priorities; higher global investment; as well as increased global cooperation and coordination.

Stern and Stiglitz (2023) also note that, in underestimating the costs of climate change, as discussed before, and overestimating the costs of policy action, mainstream studies suggest that policy action will necessarily require a "sacrifice in growth". To the extent that such a sacrifice exists, it appears to be relatively modest. For example, estimates of the costs of the transition for the United Kingdom by the Climate Change Committee have fallen over time, as the result of rapid technological progress and economies of scale in the production and diffusion of low-carbon technologies (Stern, 2022). A recent IEA report finds that clean, energy-efficient technologies are now often the most affordable, in particular in terms of lifetime cost (IEA, 2024). Arkolakis and Walsh (2024) find that moving to clean power in the United States would reduce power prices, enable an aggregate wage gain of 2-3 per cent and free up resources that could support productivity growth.

Assessing the current and future sources of productivity growth in the context of net zero policies can also provide some insights in the links between climate change and productivity. Recent measures of productivity do not yet demonstrate a transition to more sustainable growth. MFP growth – the combined efficiency of factors inputs – has been falling at the global level (Van Ark *et al.* 2023). More sustainable growth could include increased MFP growth, i.e. more output with the same inputs or the same output with less input. Moreover, global growth has relied heavily on investment in fixed (tangible) capital – buildings, structures, machinery and equipment – all of which are dependent on scarce natural resources, and not as much on intangible capital, such as R&D, data and software. Investment in intangibles – that rely mainly on knowledge and human ingenuity – has grown in many countries over the past decades, however (Van Ark *et al.* 2024). As there is no real limit to new knowledge, a shift to intangibles could be a step towards more sustainable growth. On the other hand, materials use in global production continues to rise , as do the environmental impacts associated with that use, although materials productivity is also rising. Growth today thus continues to rely heavily on tangible resources and is not yet becoming "weightless" (Quah, 1999).

Recent analysis for France suggests several potential changes in these sources of growth in the context of net zero policies.

First, the economy's capital-output ratio will likely increase due to net zero policies, linked to the higher (fixed) capital intensity of many low-carbon technologies relative to existing fossil fuel technologies (Pisani-Ferry and Mahfouz, 2023). Second, the pace and direction of technological progress will be affected, with a greater focus on low-carbon innovation. While such technological progress deviates from that driven by the market, it could be highly productive and cost-reducing, as shown by rapid progress in many key areas, such as renewables, battery technologies, electric vehicles and heat pumps, for example. Third, some of the existing stock of capital – both fixed and intangible – would become obsolete as the structure of the economy shifts. The overall impact of these changes on productivity growth is unclear and depends, for example, on whether investments in low-carbon technologies are additional to other investments or replace them, and how productive investment in low-carbon technologies is relative to existing investments.

Modelling studies can provide some further insights. Recent OECD modelling finds a relatively small cost in terms of GDP – and productivity – of policies aimed at the net zero transition (Fouré *et al.* 2023). The study finds a decline from its baseline global GDP growth of 2.3 per cent between 2019 and 2030 to 2.0 per cent, and from 2.1 per cent between 2030 and 2050 to 1.9 per cent. It notes that these macroeconomic costs should be put in context, as they do not adjust for avoided climate damages, particularly the reduced risks of climate tipping points that could not be quantified, as well as co-benefits from emissions reductions, e.g. on health (Fouré *et al.* 2023).

Scenarios developed by the Network for Greening the Financial System, a group of 127 central banks and financial supervisors, provide an additional perspective (NGFS, 2023). They point to the – relatively modest – negative cost of policy action, but also shows that policy action would have positive effects on GDP relative to a baseline of no policy action by avoiding a range of acute and chronic damages linked to climate change.

The negative impacts of climate policies on aggregate growth and productivity may therefore be relatively modest, and there may be circumstances under which the impact might even be slightly positive, e.g. when firm or countries are able to seize the opportunities associated with rapid carbonization. Moreover, most of the studies discussed above do not adjust their estimates of impacts on GDP and productivity for environmental externalities or avoided damages.

However, most of the evidence on the costs related to climate policy suggests that there are winners and losers, as is typically the case with structural reform. In the case of climate policy, productivity in highly polluting industries is more likely to be affected negatively than that in other industries. Moreover, large firms may be better able to adjust to climate policy than small firms, given their greater access to finance, and the availability of complementary factors that can help adopt new technology, such as skills, management or organizational factors.

OECD (2021) finds that environmental policies mainly entail costs for high-pollution industries and low-productivity firms, including through the detrimental effects of policy changes on laggard firms. On the other hand, more stringent environmental policies may have positive effects in improving the productivity of frontrunner firms and industries. It also concludes that the negative effects seem transitory and that environmental policies may mainly trigger a reallocation from high to low-emission industries. The study does not account for the potential beneficial effects of policies on the environment and human health, however.

Concerns in policy circles about the potential costs of policy action may also have other reasons, however. Dechezleprêtre and Sato (2017) note that firms affected by regulation may have an incentive to overstate the potential impacts on competitiveness as a strategic tool to lobby against such policies, which could allow them to take unpopular decisions to offshore or cut down on production, rather than address the underlying competitiveness problems. Moreover, as is typically the case with structural reform, the negative impacts on productivity are highly concentrated, whereas the positive impacts are more diffuse.

All of this does not imply that the transition to net zero will not be challenging for many firms, and in particular for those in industries relying heavily on fossil-fuel technologies. However, the aggregate impacts of policy actions to drive the transition on productivity may be relatively small and could be minimized by complementary policy action to address the challenge of transition, e.g. as regards access to finance, technology, skills or know-how, as discussed in the next section of this article. Crucially, policy action will require global coordination, as a large part of the positive effects of policy action in terms of avoided acute and chronic damages will depend on the global effort to reduce greenhouse gas emissions.

Climate Change Policies

Policy action to address climate change is now being taken across the world with 130 countries accounting for over 90 per cent of global GDP now publicly committed to achieving net zero.[11] Progress in reducing emissions is being made in many countries, especially through greater use of renewable energy, notably solar and wind; the phasing out of fossil fuels, notably coal; and improvements in energy efficiency combined with growing electrification. Several studies have explored how the world can achieve net zero and limit global warming. For example, the IEA's net-zero scenario provides a detailed account of the technologies that are needed to help reduce carbon emissions and achieve the goal of net zero by 2050 (IEA, 2021; 2023a).

While the global goal of net zero can be achieved in different ways, economists are broadly in agreement on the best approaches to be used (e.g. Blanchard *et*

11 Many advanced countries aim for net zero by 2050. Some emerging and developing economies have later target dates. See: https://zerotracker.net for details

12 This does not imply that there are not significant differences in view on approaches to the economics of climate change. See Stern *et al.* (2022) and Stern and Stiglitz (2023) for a discussion.

al. 2023; OECD, 2023).[12] This is because there is already considerable experience across the world in implementing climate policies and strategies, which implies that several of the key policy tools for climate action are well understood, with a significant relationship between stronger climate policy action and greater emissions reductions (Nachtigall *et al.* 2024; Stechemesser *et al.* 2024).

A first element of climate strategies are policies to level or rebalance the playing field for low-carbon products and technologies relative to incumbent, fossil-fuel based ones, by "getting prices right". Such policies seek to adjust for the negative impacts of carbon emissions on the economy by adjusting prices for the negative environmental externalities related to carbon emissions, for example, through carbon taxes, tradeable permits such as Europe's Emission Trading System and the removal of fossil fuel subsidies. Empirical evidence suggests that such policies have a strong impact on carbon emissions (Stechemesser *et al.* 2024). However, while some economists have argued that carbon pricing and the removal of fossil fuels subsidies are enough to address climate change, they are clearly insufficient on their own. There are many other market failures and barriers that affect emissions, thus requiring a broader perspective and a much wider range of policies (Stern, 2022; Sterner *et al.* 2023: Grubb *et al.* 2023).

A second element of climate policy, also strongly supported in empirical studies (Stechemesser *et al.* 2024) are actions to *strengthen and shape markets for low-carbon products and technologies* through supportive regulation, technological standards or innovative public procurement. Implementing new products and technologies can be complicated by existing rules and regulations and lack of supportive technical standards. For example, inefficient planning and permitting procedures are currently slowing down investments in wind and solar energy in many countries. Supportive regulatory policies are also key in giving clear and strong market signals (Stern, 2022), e.g. for the phasing out of carbon-intensive technologies, e.g. internal combustion engine (ICE) vehicles, or in changing consumer behaviour. Technological standards that support low-carbon innovation, for example building codes, standards for heating systems and the like, are also important.

A third important element are policies that *foster low-carbon innovation.* These policies are important to reduce the costs of the climate transition and make carbon-free technologies competitive with their high-carbon alternatives (Cervantes *et al.* 2023). Acemoglu *et al.* (2016) have shown that the complementarity of carbon taxes and innovation policies allows for much lower carbon taxes, thus reducing the costs of policy action.

The economic literature points to several barriers and market failures that discourage low-carbon innovation, and therefore finds strong economic justifications for policies that seek to overcome these barriers.[13] Such policies may focus on im-

13 See Cervantes *et al.* (2023) for an overview and discussion.

proving the business environment for innovation, e.g. through competition or skills policies. They may also include more specific innovation policies such as investment in public R&D or tax incentives and grants to investment in business R&D. Detailed empirical analysis for 22 OECD countries shows that innovation policies such as R&D tax credits and direct support (e.g. grants) have a positive impact, with one extra unit of R&D support translating into 1.4 extra units of R&D (Appelt *et al.* 2023). These impacts are expected to be higher for low-carbon innovation as empirical studies have estimated that knowledge spillovers for low-carbon technologies are 60 per cent higher than for high-carbon technologies, given their relative novelty (Dechezleprêtre, Martin and Mohnen, 2014).

A fourth key element are policies that *mobilize investment and finance* for low-carbon activities and technologies. Establishing ambitious and stringent long-term climate policy frameworks is important to send a strong signal to investors and financial markets about the future of low-carbon assets (OECD, 2023). Policies to reduce investor risk, e.g. by risk insurance and guarantees, are important to, as are policies to reduce regulatory barriers to investment.

A fifth key element are policies that *support and facilitate the necessary structural change and resource allocation* and allow for a smooth and fair transition for displaced workers. This requires labour markets that facilitate the transition for workers and investment in new "green" skills, including advanced technical skills to help develop new technologies, but also skills to use and service new technologies, and use them across society. Investing in such skills will not only support innovation but will also help people make the transition in the labour market, helping them move from declining industries – such as fossil fuel-based ones – to emerging and growing industries such as renewable energy, recycling and environmental services.

Policies in support of structural change will also need to consider the distributional impacts of policy action, as there is a risk that the poorest households, communities and countries will be hit hardest without supporting policy action. Integrating these concerns in key policies, such as the design of carbon taxes, the removal of fossil-fuel subsidies, support programmes, or education and training, will be key to ensuring a transition that is perceived as fair. An important challenge in this context is that structural change will have to play out over a very short period compared to previous periods of deep structural change, and affect every individual, country, industry and firm.

A final, but crucial, element are policies that address the *global dimensions of climate change*, including supportive trade policies, international science and technology cooperation and policies that support investment in low-income economies and help them adjust to climate change. One challenging aspect are carbon border adjustment measures where jurisdictions apply import fees based on the carbon content of imported goods, reflecting the difference in carbon pricing between that jurisdiction and the exporting country (Clausing and Wolfram, 2023). Such measures are intended to address carbon leakage, i.e. emissions increasing in foreign jurisdictions because of stringent domestic climate policies.

Global action is also central to achieving positive impacts on GDP and well-being at the national level. While individual countries have good reasons to take actions at the national level and should see positive returns from that as regards innovation, adaptation and resilience, the greatest benefits from policy action occur when all countries reduce emissions, thus limiting damages and creating an environment that encourages innovation and structural change.

Productivity Policies and Climate Change

The question is how these climate change policies align with the policies that are generally considered to support productivity growth. As explored by Van Ark, de Vries and Pilat (2023), pro-productivity policies typically include actions to: a) support investment and factor accumulation; b) foster innovation and structural change; c) make markets work and encourage resource allocation; d) facilitate internationalisation; as well as e) foundational policies.

Addressing climate change in the context of pro-productivity policies does not necessarily change the policy tools that governments use to strengthen productivity growth but changes what tools are being applied and how they are being applied, and what complementary tools are being used to address climate change. For example, as discussed already, the overarching objective of addressing climate change and reaching net zero will require much greater emphasis on policies that improve the functioning of markets by getting "prices right" and adjusting for the negative externalities related to fossil fuels. It will also require much greater directionality of the innovation process to encourage low-carbon innovation (Cervantes *et al.* 2023), foster new firms and industries, promote investment in specific areas (e.g. renewable energy, infrastructure, clean transport) and support specific skills. Other elements that will require greater emphasis included the management and restoration of natural capital; ensuring the resilience of existing infrastructure; and access to capital, amongst others (Bowen *et al.* 2012). Sector-specific policies will also be required, e.g. to strengthen resilience in agriculture, and aimed at adaptation to climate change.

The policies required for the transition to net zero deviate in several ways from the standard framework for pro-productivity policies, as they are intended to guide the (global) economy towards a specific goal, i.e. net zero emissions. In principle, these deviations should lead to lower productivity growth than the default set of pro-productivity policies. However, it is not clear what such a default or counterfactual implies in practice, as it assumes no impact of climate change on GDP and productivity. The only credible scenarios are policies that address climate change, while supporting productivity and income growth to the best possible extent.

That does not mean there are no trade-offs between climate change policies and pro-productivity policies. However, good policy design can help reduce the potential negative impacts of climate change policies on productivity, e.g. by ensuring that such policies build on well-functioning markets and clear price signals; that competition and trade openness are maintained; by fostering international cooperation and coordination; and by making innovation policies a central component of the policy package, as such policies can help accelerate the transition, reduce the costs of policy action and support productivity (Cervantes *et al.* 2023).

In principle, economic policies should be designed to meet the target of net zero in the most efficient way, with the least possible costs. At the same time, the path for emissions reductions matters, as the economic and social impacts of climate change will increase with the time needed for the transition and the volume of greenhouse gases that is emitted before net zero is reached. This implies that economic efficiency is not the only – and perhaps not always the most important – criterion for policies to address climate change.

Main Findings and Conclusions

This article aimed to help clarify the ongoing debate about the impacts of climate change on productivity. A first finding is that the analysis of climate change requires a wider set of measures than standard productivity analysis, i.e. not just measures of labour and multi-factor productivity. On the one hand, it is important to distinguish between impacts of climate change on productivity measures that are closely associated with economic performance (e.g. labour and multi-factor productivity, either adjusted or not adjusted for environmental externalities). On the other hand, it is crucial to also explore productivity measures that are associated with the physical and natural processes linked to climate change (e.g. materials, energy and carbon emissions productivity, and the role of natural capital and the ecosystem as a whole). While much of the debate on productivity and climate change has focused on economic performance, improving productivity in the use of materials, resources and natural capital is central to achieving net zero and requires much greater emphasis in the debate on climate change and in the measurement and analysis of productivity.

This will require improvements in the current – incomplete and inadequate – state of productivity measurement, and its use in analysis and policy. While credible alternatives and complements to GDP and standard measures of productivity have been available for some time, including measures of environmentally adjusted productivity, as well as measures of natural capital, these have not yet been sufficiently developed and integrated to become the default for work in this area. Particularly important are the development of natural capital accounts (Agarwala *et al.* 2023) and their integration in the policy making process (Guerry *et al.* 2015); the use of environmentally-adjusted measures of productivity that incorporate shadow prices (Brandt *et al.* 2017; Cárdenas Rodríguez *et al.* 2018, 2023; Agarwala and Martin, 2022); greater attention for the full range of productivity measures, including materials, energy and carbon emissions productivity, rather than only measures of labour and multi-factor productivity; more KLEMS productivity studies that include energy and materials; and a greater focus on well-being, rather than just GDP (Van den Bergh, 2017). Some of these areas still require further methodological development. However, not integrating them in the policy debate on climate change risks biased and incomplete evidence for decision makers.

In examining the evidence on productivity growth, the article finds that mainstream economic studies over the past few decades have significantly underestimated the damaging impacts of climate change on GDP and productivity, due to a range of methodological limitations and deficiencies and by ignoring the growing risks of the climate passing tipping points.

The article also finds that while there has been substantial productivity growth in the use of certain natural resources in advanced economies, including energy, materials and carbon emissions, the current pace of decoupling of GDP from the use of these natural resources is much below of what is required to meet net zero climate goals. Productivity growth in countries that have already achieved high productivity levels in the use of natural resources will still need to double or treble compared to growth rates achieved over the past decades, whereas countries with lower productivity levels will need to achieve even higher growth rates in the future. Better understanding the drivers of such productivity growth could benefit from more productivity research focused on resources and materials.

Standard measures of productivity also do not yet demonstrate a transition to more sustainable growth. Multi-factor productivity growth – the combined efficiency of factors inputs – has been falling at the global level, and the transition to net zero will likely require large investments in fixed capital, and not just intangible and human capital. With global material use continuing to grow, growth and productivity are clearly not yet becoming "weightless" or green.

In examining the impacts of climate-related policies on productivity, the article finds that studies today may well overestimate the long-term costs of policy action to address climate change, in ignoring the dynamic effects of global policy action on innovation, economies of scale and learning-by-doing, including the rapidly falling costs of key green technologies, and in comparing outcomes with a wrong counterfactual. If there is no long-term trade-off between growth and climate, economic studies may have held back the case for economically and socially positive policy action to address climate change.

The main policy challenge is how to design climate change policies to meet the global objective of net zero – where it will be essential to meet this goal in the shortest possible timeframe to reduce the overall volume of greenhouse gas emissions – while also supporting productivity and well-being. To meet this challenge, governments will need to shape markets for low-carbon products and services, notably in adjusting for environmental externalities by carbon taxation, emissions trading and the removal of fossil fuel subsidies, and by regulation and standards. They will also need to give direction to technological change to accelerate low-carbon innovation and foster the uptake and diffusion of low-carbon technologies. Innovation policies are particularly important, as they can complement carbon taxation and help bring down the cost of policy action, and support productivity growth. Climate change policies will also need to facilitate the necessary structural change, and provide for a fair transition, both for social groups that may be most affected in the process, and for developing countries that will be most affected by climate change.

A final conclusion is that economists in general, and those working on productivity in particular, should engage much more with the debate on climate change and its links to economic growth, productivity and well-being. Such engagement will require much greater cooperation with other disciplines, including climate science. National productivity commissions and other analysts focusing on productivity growth may also want to broaden their monitoring, reporting and analysis to a wider set of productivity measures.

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Using Ecosystem Accounting to Integrate the Environment in Measures of Multifactor Productivity

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Abstract

There is increasing recognition of the relevance of integrating environmental considerations within standard macroeconomic measures including GDP and national wealth and, by extension to measures of multifactor productivity (MFP). A range of approaches to measuring environmentally adjusted MFP (EAMFP) have been developed over the past decade which variously adjust the measure of output or recognize explicitly natural capital inputs. This article summarizes the main approaches to EAMFP and discusses their merits from a national accounting principles perspective, identifying some concerns on potential double counting of environmental contributions and effects. It then considers the potential of ecosystem accounting as described in the System of Environmental-Economic Accounting (SEEA) Ecosystem Accounting to offer an alternative framing for integrating the environment into economy-wide MFP measures.

The ongoing realities of climate change and the increasing pressure on biodiversity are significant risks to global economic and social systems. The number of reports highlighting the economic significance of these changing circumstances are numerous. To pick just one, in their 2020 report *Nature Risks Rising* (WEF, 2020), the World Economic Forum concluded that around 50 per cent of the global economy is moderately to highly dependent on nature. This, and other reports, highlight that ignoring the economy's connection to the environment or continuing to treat the environment as able to provide an endless supply of free environmental services is not

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just risky but poor economics. Developing an information set that supports more comprehensive economic analysis must be a core part of the collective response to our environmental challenges.

Over the past 15 years, significant steps have been taken in developing such an information set through the statistical standards embodied in the United Nations System of Environmental-Economic Accounting (SEEA). In 2012, the United Nations Statistical Commission adopted the SEEA Central Framework (UN *et al.*,2014) and in 2021 they adopted the SEEA Ecosystem Accounting (UN *et al.*, 2021). Together with a range of supporting materials, these statistical frameworks provide the structure for the organization of a wide range of environmental data that complements and extends the standard economic data organized following the System of National Accounts (SNA) (UN *et al*, 2010).

However, the development of structured environmental-economic information frameworks and datasets does not of itself lead to better and more integrated economic analysis. In the field of productivity analysis, most work remains focused on standard labour and multifactor productivity measurement and resolving a range of measurement challenges: some that are long-standing such as concerning public sector output and some emerging as the economic system continues to evolve, such as digitalization. A focus on incorporating environmental issues has not been central. Indeed, in a 2019 review article of the *Oxford Handbook of Productivity Analysis* (Reinsdorf, 2019), the word "environment" does not appear.

The explicit incorporation of environmental considerations into industry and economy wide productivity measures would support a more complete understanding of the factors that drive output and inputs growth and hence support the development of more integrated policy responses. Positively, there is an increasing number of examples of research on incorporating the environment into productivity analysis.

To further motivate this trend, Section 1 commences with a description of the main entry points that have been investigated in the development of environmentally adjusted multifactor productivity (EAMFP) measures. Section 2 then summarizes the key aspects of the SEEA framework that support the organization of information for the derivation of EAMFP. Section 3 discusses the challenges of connecting current EAMFP approaches to standard growth accounting theory and the national accounting principles that support implementation of the theory. Section 4 offers an alternative approach to economy wide MFP measurement that takes advantage of the extension to the SNA production boundary described in the SEEA Ecosystem Accounting. Section 5 demonstrates the alternative ecosystem accounting based approach with a stylized example. Section 6 concludes highlighting some key areas for future research.

Entry Points to Incorporating the Environment in Economy-Wide Productivity Analysis

A key driver in the development of measures of economy-wide MFP over the past 70 years has been the link between the growth accounting approach to the measurement of MFP and the ongoing compilation of the national accounts following the SNA. In basic terms, the growth accounting approach involves comparing the growth of output measured in quantity or volume terms to the growth of inputs, such as capital and labour, also measured in volume terms. To the extent that the growth in output is greater than the growth in combined inputs, then productivity growth, defined as MFP, is positive.

This approach relies on a number of assumptions including that producers behave efficiently (i.e. they minimize costs and/or maximise revenues) and that markets are competitive (see OECD, 2001 for more details). Under these assumptions, it is possible to construct an index of combined inputs using the factor income or cost shares as weights. That is, the index of combined inputs is calculated by weighting the changes in quantity of each type of input by the share of total costs for each input.

The link to national accounts emerges in two ways. First, a standard data release from national accounting systems are measures of volume indexes for output and inputs across different industries and products. Most commonly these volume indexes are estimated by deflating nominal measures of gross output and input costs by relevant price indexes. Subsequently, volume indexes of gross value added (GVA) can be derived. Second, another standard data release from national accounting systems are measures in nominal terms which provide the basis for the estimation of cost shares. Thus, the measures of gross output, GVA, intermediate consumption, compensation of employees, gross operating surplus and capital stock that are provided on an annual basis for most countries provides a rich and coherent data set for analysis of productivity.

Importantly, concerning measures in nominal terms there is an underpinning additive relationship between the inputs to production and the outputs of production. This allows the appropriate weighting of the contributions from labour and capital to GVA such that the residual, the unexplained growth in output that constitutes MFP in the growth accounting approach, to be meaningfully appraised.

Through input-output tables the national accounting system takes these additive relationships further supporting coherent measurement of the links between labour, capital and GVA and also supporting the measurement of KLEMS-based measures of MFP which do not use GVA as the measure of output but rather explicitly incorporate gross output and the various intermediate inputs such as energy, materials and services (E, M, S) in addition to inputs of capital (K) and labour (L).

In stylized terms we thus have the following accounting relationships that underpin the measurement of MFP. Note that, recalling the discussion above, the relationships described here (and in subsequent equations) must be measured using volume indexes for each component with MFP reflecting the growth rate in output, either value added or gross output, relative to the growth rate of combined inputs on the right hand side weighted using their cost shares.

$$\text{GVA} = K + L + \text{MFP} \qquad (1)$$

$$\text{Gross Output} = K + L + E + M + S + \text{MFP} \quad (2)$$

These two equations are equivalent since GVA is equal to gross output less intermediate consumption (i.e. E + M + S).

As summarized in the OECD Productivity Manual (OECD, 2001: 18):

> "The economic theory of productivity measurement goes back to the work of Jan Tinbergen (1942) and independently, to Robert Solow (1957). They formulated productivity measures in a production function context and linked them to the analysis of economic growth. The field has developed considerably since, in particular following major contributions by Dale Jorgenson, Zvi Griliches and Erwin Diewert. Today, the production theoretical approach to productivity measurement offers a consistent and well-founded approach that integrates the theory of the firm, index number theory and national accounts."

Unfortunately, most current practices of productivity measurement omit the role of natural resources and ecosystem services as inputs into production and do not account explicitly for the effects of environmental pollution. By way of example, in measuring the productivity of the agricultural industry, some countries recognize land as an input but only in terms of its area; factors such as its quality (e.g. in terms of soil fertility) and the input of water are not considered. The depletion of mineral and energy resources is similarly omitted in assessing mining productivity (Syed, Grafton, Kaliappa and Parham, 2015).

This is not to say that the relevance of the environment in productivity analysis has been completely overlooked. Over the past 50 years there have been a range of efforts to examine the connections. There are four main entry points that have been used to adjust the standard growth accounting equations noted above.

Bad Outputs

The first entry point involves accounting for undesirable or bad outputs that arise from production processes such as air and water pollution often in the context of joint production models (Shephard (1970) and Färe *et al.* (1989)). This work has been most extensively developed by the OECD over the past 10 years. Brandt *et al.* (2014) develop their environmentally adjusted MFP (EAMFP) measure by deducting from GVA the effects of three air emissions sulphur oxides, nitrogen oxides and carbon dioxide. Subsequent work by Cardenas Rodriguez *et al.* (2018), Agarwala *et al.* (2022) and Cardenas Rodriguez *et al.* (2023) have progressively expanded the range of air emissions and the level of industry detail at which calculations are undertaken. In all of these cases the measure of an environmental bad is deducted from GVA in the MFP equation. Thus, in simple terms

$$\text{GVA} - \text{Environmental bads} = K + L + \text{MFP} \quad (3)$$

Natural Capital Inputs

The second entry point concerns recognition of natural capital inputs. This entry point recognizes that conceptually the K in the MFP equation reflects the contribution of both produced and natural capital. For many years a number of countries have included land as an input to the capital contribution in agriculture but, in terms of standard practice, this has not been extended to other industries where natural capital is a fundamental input.

Positively, work by Brandt *et al.* (2013) and Topp and Kulys (2014) explain well the relevance and potential of adjusting standard productivity measures for natural resource inputs. Brandt *et al.* focus on the user costs of depleting mineral and energy resources in assessing productivity of the mining industry. Topp and Kulys consider also rainfall as an input to agriculture and noted the shift in Australia from using rain-fed dams to underpin water supply towards increasing use of produced capital such as via desalination and water recycling. Hamilton *et al.* (2018) build on the work of Brandt *et al.* (2013) in the context of the wider work of the World Bank in measuring national wealth.

The most recent additions to this suite of natural capital input adjustments are included in the latest version of the OECD EAMFP model (Cardenas Rodriguez *et al.*, 2023) which includes natural capital inputs covering land resources, non-renewable mineral and energy resources, biological resources (timber and fish), three ecosystem services (watershed protection, non-wood forest products and coastal flooding protection) and three renewable energy resource inputs (hydro, wind and solar).

The resulting simple growth accounting equation is reflected as

$$\text{GVA} = K^P + K^N + L + \text{MFP} \qquad (4)$$

where K^P refers to produced capital and K^N refers to natural capital.

In this framing, the effect of including K^N is to more appropriately recognize the role of natural capital recognizing that the non-labour share is the same in both equations (1) and (4). In accounting terms this represents the partitioning of gross operating surplus into a return to produced capital and a return to natural capital. MFP will be affected to the extent that the volume growth rate of natural capital is different from the growth rate of produced capital.

Since the natural capital inputs are treated as non-produced (e.g. arising from the discovery of a mineral deposit) there is no associated change in GVA. However, changes in the stock of natural capital may have effects on the cost of natural capital but the growth in K^N, and hence MFP, is driven primarily by rates of extraction and use of natural capital rather than overall changes in the size of the physical stock.

Environmental Expenditures

A third entry point to adjusting the growth accounting equation has been investigated in Agarwala *et al.* (2022). They propose a positive adjustment to GVA by treating environmental expenditures as additional output as a proxy for the improvements in environmental outcomes that arise from undertaking this expenditure. Put differently, without recognizing an increase in gross output, expenditure on the environment will reduce MFP growth, all else being equal. The effect of raising the measure of gross output leads to the productivity equation shown in equation (5).

$$\text{GVA} + \text{Environmental expenditures} = K + L + \text{MFP} \quad (5)$$

Combinations of these three entry points are also possible and indeed the full OECD EAMFP model combines entry points 1 and 2 as reflected in equation (6) using the stylized notation applied here.

$$\text{GVA} - \text{Environmental bads} = K^P + K^N + L + \text{MFP} \quad (6)$$

Conditional Measures of MFP

A fourth entry point is formulated in Schreyer (2021). That article returns to equations (1) and (2) and, recognizing that the underlying relationships in growth accounting are linked to production theory, describes a cost function that is conditional on ecosystem services. In this case there is no necessary accounting or additive relationship between the ecosystem services and the standard combined inputs but an alternative measure of MFP, conditional on changes in the flows of ecosystem services, is still derived. This entry point is not considered further in this article since it has no direct link to the extended accounting approaches that are the focus here, but is recognized to highlight the range of different approaches that might be developed.

Environmental Adjusted MFP for Agriculture

Separately from the work on economy-wide measures of MFP, experts in measuring the agriculture industry have well established measures of productivity. The approaches range from farm-level analysis to national and international level studies and encompass econometric and non-parametric approaches to MFP measurement in addition to growth accounting. In 2015, the OECD commenced a program of work on improved measures of agricultural MFP and papers by Hoang (2015) and Kuosmanen (2015) summarized the state of play.

Generally, the focus of environmentally-adjusted agriculture MFP measures has been to consider adjustment of standard MFP measures for specific environmental factors including land, the impacts of nitrogen (N) and phosphorous (P), residuals and by-products from agricultural activities, including GHG emissions, and the impacts of changes in weather patterns, for example due to climate change. This work has generally reflected the use of the first two entry points described above, i.e., adjusting for bad outputs and adjusting for natural resource inputs, primarily land.

This article does not attempt a wider review of these methods except to note that there is a close conceptual link between the approaches used by agricultural experts in, for example, the United States (Ball *et al.*, 2014), Canada (Cahill & Rich, 2012) and Australia (Zhao *et al.*, 2012) and the economy-wide growth accounting described above. And there is associated work to consider environmental-adjusted measures of agricultural productivity that reflect the types of adjustments just described as recently summarized by OECD (2022). Given these links, and building on the ideas of Obst and Eigenraam (2017) concerning environmentally adjusted MFP measures for agriculture, the discussion in this article should be broadly amenable to consideration by those industry experts.

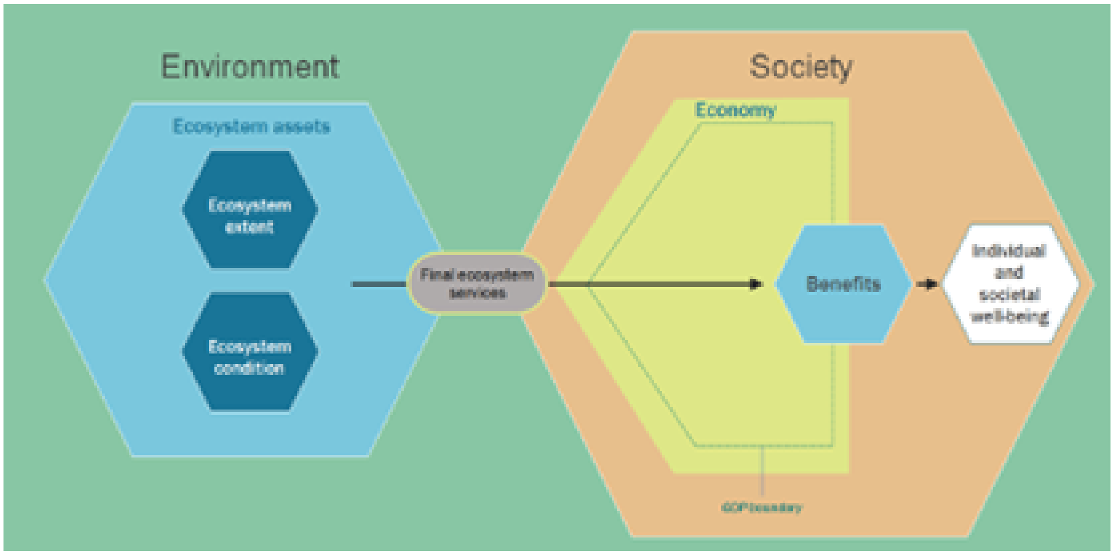
Expanding the Information Set to Support EAMFP

The need to better integrate measures of the environment within the national accounts framework was increasingly recognized through the 1970s and 1980s (Bartelmus, 1987; Ahmad *et al.*, 1989). Consistent with a request from the first United Nations Conference on Environment and Development held in Rio de Janeiro in 1992 (United Nations, 1992), the United Nations Statistical Division led the drafting of the first international document on environmental-economic accounting (United Nations, 1993). This document, *Handbook on National Accounting: Integrated Environmental and Economic Accounting*, became known as the System of Environmental-Economic Accounting or SEEA.

Over the past 30 years there has been a progressive broadening of focus in SEEA related work. Through the 1980s and early 1990s, the primary focus was on extensions and adjustments to gross domestic product (GDP), for example measures of depletion and degradation adjusted GDP, and recording environmental expenditures. Through the 1990s this focus broadened to consider how accounting approaches can be used to organize physical information on environmental stocks and flows such as water, energy and waste. Also through the 1990s, and in parallel with similar developments in the SNA, the SEEA delved deeper into accounting for individual natural resources including mineral and energy resources, timber, fish and land. This combination of topics was embodied in the first international statistical standard for environmental-economic accounting adopted in 2012, the SEEA Central Framework (UN *et al.*, 2014).

The more recent and conceptually most progressive development concerns ecosystem accounting as a complement to accounting for individual environmental stocks and flows in the SEEA Central Framework. Work on the SEEA Ecosystem Accounting (UN *et al.*, 2021) commenced in 2011 and took advantage of developments in the measurement of ecosystem services, such as presented in the report of the United Nations *Millennium Ecosystem Assessment* (MA, 2005), the original The Economics of Ecosystems and Biodiversity (TEEB) study (TEEB, 2010) commissioned by the German Environment Minister and the EU Environment Commissioner, and the National Ecosystem Assessment of the United Kingdom (UK NEA, 2011). In 2021, the SEEA Ecosystem Accounting framework (Figure 1) was adopted by the United Nations and notwithstanding its short life, it is now recognized across the private and public sectors as the leading framework for linking the economy and the environment for the

Figure 1: General Ecosystem Accounting Model (SEEA EA Figure 2.1)



Source: UN *et al.*, 2021

purposes of economic and financial analysis. [2]

Both the SEEA Central Framework and SEEA Ecosystem Accounting are connected to the SNA through their application and adaptation of national accounting principles and treatments. Indeed, the logic driving the development of the SEEA is (i) that the SNA's accounting for the environment is insufficient; and (ii) that highlighting the significance of the environment may be best achieved by mainstreaming environmental information via the standard framework for economic measurement. In the context of productivity analysis, since it is the data from the SNA that underpins the standard measures of MFP, it is equally the concepts in the SEEA that can provide a fundamental building block towards environmentally- adjusted measures of MFP.

Ecosystem accounting is focused on accounting for ecosystem assets – their extent (or size), their condition (or health) and the ecosystem services they supply. The full ecosystem accounting model is described at length in Chapter 2 of SEEA Ecosystem Accounting and readers are referred to that document for a detailed description.[3]

Five key features of the ecosystem accounting model are noted:

- **The delineation of spatial areas.** Within a broader ecosystem accounting area (e.g. a country, state, water catchment), each ecosystem asset (e.g. a grassland, forest, coastal dune, coral reef, cropland) is delineated as a distinct spatial area. For the purposes of integrating ecosystem information about ecosystem assets with standard economic accounts and

2 For additional context on the development of the SEEA Ecosystem Accounting, see Edens *et al.* (2022).

3 The references section of the SEEA Ecosystem Accounting provides an extensive listing of the literature on which the various aspects of the ecosystem accounting model have been based. This includes research in relation to ecosystem condition, ecosystem services, ecological economics, geospatial statistics and national accounting.

productivity measures, it is most useful to consider each ecosystem asset as a type of economic unit, analogous to a single business or household. In effect, ecosystem accounting extends the set of units considered in an accounting framework beyond the standard economic units.

- **Measuring the condition of ecosystem assets.** Each ecosystem asset has numerous characteristics (such as climate, soil, vegetation, species diversity, etc.) and performs various ecosystem processes. The integrity and functioning of the asset is measured by its condition. It is the decline in overall condition, in biophysical terms, that underpins the measurement of ecosystem degradation.

- **Measuring the flow of ecosystem services.** Each ecosystem asset supplies a basket of ecosystem services that are consumed by different economic units including businesses, households and governments. These flows between ecosystems and economic units can be recorded in supply and use tables analogously to flows of goods and services between industries. The coverage of ecosystem services includes provisioning services (e.g. food, fibre, water), regulating and maintenance services (e.g. air filtration, pollination, water flow regulation, global climate regulation) and cultural services (e.g. recreation).

- **Relating ecosystem services to standard measures of economic activity.** The supply of all ecosystem services is outside the production boundary of the SNA as they are considered to arise from natural processes (SNA 2008, 6.24). At the same time, many ecosystem services contribute to the production of goods and services that are included in the SNA production boundary, for example the contribution of water to rice production. To understand the impact on measures of GDP, it is necessary to recall that GDP is a measure of value added – i.e. gross output less intermediate inputs. Thus, where ecosystem services contribute to existing measures of gross output (e.g. to the production of crops), the net effect on GDP and MFP of recording both the supply and use of ecosystem services is zero, since the ecosystem services are considered both as additional outputs (of the ecosystem asset) and additional inputs (of the farmer).[4] Where ecosystem services are not an input to the production of goods and services included in the SNA production boundary, the additional output that is attributable to ecosystem assets will increase measures of both economy-wide gross output and value added.

- **The use of exchange values.** The ecosystem accounting model reflects relationships between stocks and flows that exist without regard for the unit of measurement. Thus, in concept, the accounting relationships can be reported in both physical and monetary units. Measurement in monetary terms requires the use of various valuation techniques since prices for ecosystem services and assets are not directly observed in markets as for standard economic products. To support connection

4 Note that it is by recognizing ecosystem services as both outputs (of ecosystem assets) and inputs (to farming units) that double counting is avoided. The treatment is exactly analogous to the treatment of outputs and inputs through the supply chains recorded in standard input-output tables.

to the data in the national accounts, measures in monetary terms are recorded at their exchange value by estimating (using non-market valuation methods) the prices at which a willing buyer and willing seller would complete a transaction in a single ecosystem service.

These five key elements of ecosystem accounting provide the conceptual basis for extending the current approaches to measuring MFP.

Evaluating EAMFP Measures in Relation to Accounting Data

Starting from the OECD's EAMFP model as expressed in equation (6), there are direct connections that can be made to the SEEA framework as summarized above. Purely from the perspective of providing data inputs to the calculation of EAMFP, the following SEEA accounts will support the compilation of robust data that are consistent with standard national accounting treatments and with other components of the EAMFP calculation, namely GVA, produced capital and labour.

- SEEA Central Framework Air emissions accounts
- SEEA Central Framework Land accounts
- SEEA Central Framework Natural resource accounts for mineral and energy resources, timber resources, fish resources
- SEEA Central Framework Energy accounts for renewable energy resources
- SEEA Ecosystem Accounting Ecosystem services supply and use tables.

While the SEEA framework can supply the data ingredients, there are two significant concerns relating to the underlying relationship between the components within equation (6). Recall from section 2 that a key feature of the application of the growth accounting approach to the measurement of MFP has been application of the additive relationships between the output and input variables that are inherent in the national accounts system, including the input-output tables. The concerns, one relating to the treatment of ecosystem services in the measurement of natural capital inputs and one related to environmental bads, arise because the underlying additive accounting relationships are not maintained in the EAMFP equation.[5]

Before discussing these concerns, note that, the additive accounting relationship can be maintained provided that the calculation includes only those natural capital inputs which contribute directly to GVA and gross output as defined in equations (1) and (2), for example, inputs of minerals, timber and fish. In the context of the OECD EAMFP model, this direct link is evident for all inputs from non-renewable fossil fuel and mineral resources (reflected in output of the mining industry), for inputs of renewable energy resources (reflected in output of the electricity industry), for inputs from cropland and pastureland, from timber resources and from marine capture fisheries (all reflected in outputs of the agriculture, forestry and fish-

5 Note that the discussion here does not encompass an evaluation of the fourth entry point noted in the first section of the article from Schreyer (2021).

eries industries). All of these natural capital resources are referred to in the SEEA Central Framework as individual natural resources.

The accounting relationship involving natural capital and other inputs has been well developed in the capital accounting literature and is evident in the work cited above, for example, Brandt *et al.* (2013) and Hamilton (2018). It reflects a much wider literature on this topic in the context of wealth accounting [6] The application of this theory to national accounting and the SEEA has been embodied in work by Schreyer and Obst (2015) and research conducted separately by Fenichel and Abbot (2014) who applied the underlying Jorgenson capital accounting framework to the valuation of natural capital, in essence finding that an analogy between accounting for natural and produced capital can be established.[7]

Evaluating the Inclusion of Ecosystem Services

The first concern about additivity in the EAMFP equation relates to the way in which ecosystem services have been included. Cardenas Rodriguez *et al.* (2023) explain that they have included three ecosystem services – non-wood forest products and watershed protection from forests and coastal flooding protection from mangroves – and note that they would ideally have included many other ecosystem services including recreation, habitat and species protection and cultural and existence values but data and valuation limitations prevented their inclusion.

It is certainly the case that ecosystem services can be incorporated into the measurement of natural capital following the wealth accounting theory just referenced. Indeed, Eigenraam and Obst (2018) explain the analogous conception of ecosystem services and capital services from produced capital. However, incorporation of ecosystem services within a wider model must consider (a) overlap with other measures of natural capital; and (b) links to the production boundary of the SNA.

With respect to point (a), the SEEA makes clear that accounting for ecosystem assets and accounting for individual natural resources are complementary areas of measurement, not additive. Thus, for example, the value of a forest will encompass its supply of a range of ecosystem services including the supply of wood. There is thus a potential overlap that needs to be managed, i.e. values of individual natural resources (e.g. timber resources) and ecosystem assets (e.g. forests) cannot be simply added together. The current selection of ecosystem services in the OECD EAMFP appears to avoid this overlap but this issue will need to be recognized in future work.

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6 See, for example, Hamilton and Clemens (1998), Dasgupta and Maler (2000); Arrow *et al.* (2012), Hamilton (2015) and Diewert and Fox (2015).

7 Strictly, ecosystem accounting does not include inputs from non-renewable resources or inputs from renewable energy sources since these inputs are considered abiotic flows rather than ecosystem services. However, in a wider accounting context and for the purposes of productivity analysis, abiotic flows and ecosystem services can be aggregated within the same accounting framework and in the following discussion the two inputs are accounted for analogously.

A related issue is where ecosystem services are intermediate (for example pollination as an input to crop provisioning or nursery services as an input to fish provisioning) since here simple aggregation of all services will miss the inherent ecosystem supply chain (input-output type) interactions and hence overstate the overall ecosystem contribution.

With respect to point (b), the OECD EAMFP approach implicitly assumes that the ecosystem services are contributions to the production of goods and services that are within the SNA production boundary. This is appropriate in the context of non-wood forest products (e.g. mushrooms, berries, maple syrup, cork, bush meat), but cannot be assumed in the case of watershed protection or coastal flooding protection. That is to say that these two ecosystem services contribute to benefits received by people and society that are beyond the scope of the goods and services measured within GDP. To the extent that this occurs, then the natural capital inputs in equation (6) will not be matched by a corresponding output and, all else equal, EAMFP will be understated.

Evaluating the Deduction of Environmental Bads

The second concern relates to the deduction of environmental bads. No doubt there is an economic argument to support the case that measured output should be adjusted to take into consideration the negative externalities arising from production. However, in accounting terms it is not a simple matter of deducting bad outputs from good outputs and indeed, the SNA is quite explicit about not accounting for externalities and GDP not being interpreted as a measure of welfare.

The accounting challenge arises because the additive accounting relationships depend on recording transactions between economic units. In a national accounting sense this requires that there is both a supply and a use for each transaction. In the case of pollution, while the flow of pollutants no doubt comes from an economic unit, there is no corresponding receiver. In effect the question of the environmental bad is being considered from the perspective of one unit only and national accounting requires a more comprehensive framing.

A particular concern in simply deducting environmental bads from output is that it may double count the effects. Consider the case where air pollution by one company leads to increased costs to nearby building owners either through higher maintenance costs or lower rentals incomes. In the economy-wide accounts these increased costs to the building owner will be reflected in measures of GVA – i.e. GVA will be lower all else being equal. Additional deduction of bad outputs from the GVA of the polluter would overstate some of the effect of the pollution. The extent to which there is a double counting of the negative effects of the air pollution (or any other environmental bad) will be dependent on a wide range of contextual factors. Indeed, to the extent that the pollution has no effect on other economic units, then the question must be raised as to why the release of the pollutant should be considered as a negative.

The approach of Brandt *et al.* (2013) addresses this issue to some degree by applying a private valuation of the "bads" by weighting them with the measure of "good" output using marginal abatement costs as seen by the producer. Inherent in this approach is the assumption that increasing good output necessarily involves increasing bad output. This in turn has the effect of constraining the concerns described above to the polluter. At the same time however, the approach then does not reveal the wider implications of bad outputs on the wider economy.

The key point here is that care is needed in using an approach that deducts bad outputs and, in doing so, considering the accounting relationships between inputs and outputs can be an important tool in developing and interpreting alternative approaches.

Note that this concern is not limited to the current OECD EAMFP model, but is relevant in considering all approaches where GVA is adjusted by an environmental bad as part of an extended growth accounting approach.

An Alternative Approach to Extending MFP Measures

A common feature of the environmentally-adjusted measures described in Section 2 is that all adjust GVA and hence the measure of output in the MFP equation is equal to value added rather gross output. This is significant since without a full articulation of inputs and outputs across all industries, the connection to the environment is only seen in terms of either (a) a natural capital input; or (b) a negative impact on the environment. Consequently, and as introduced in Section 3, connections between industries (e.g. the effects of pollution on other activities) or between natural inputs and produced inputs (e.g. the trade-offs between fertilizer and soil fertility) cannot be examined in the richness that the underlying economic theory would prefer. This section describes an approach that embodies this richness and incorporates the additive accounting relationships that are considered essential in applying growth accounting approaches. The approach builds on initial thinking proposed by Obst and Eigenraam (2017) in the context of agricultural productivity.

At the heart of the alternative approach is the combination of the KLEMS approach to MFP reflected in equation (2) and the ecosystem accounting framework depicted in Figure 1. Recalling that the measurement of MFP will require calculation of volume indexes for combined outputs and inputs weighted by their nominal output and cost shares, equation (7) presents the core Ecosystem MFP model

$$\text{Gross Output (SNA)}+\text{Output (Ecosystem services)} = K^P + K^E + K^{NR} + L + E + M + S + \text{Input (Ecosystem services)} + \text{MFP} \quad (7)$$

where K^P refers to produced capital, K^E refers to ecosystem assets (encompassing renewable resources such as timber and fish), K^{NR} refers to non-renewable natural resources and L, E, M and S are as per the standard KLEMS model.

In short, the Ecosystem MFP model extends the production boundary of the SNA and allows explicit recognition of all ecosystem service contributions (via K^E) and records all flows of ecosystem services between ecosystems and economic units arising as a result of these ecosystem service contributions (via the inclusion of outputs and inputs of ecosystem services). While this may appear to "over-record" the flows associated with ecosystem assets, the example below demonstrates the relevance of this all-encompassing approach.

In relation to the two concerns raised above, this approach will ensure (i) that there is no double counting of components of natural capital since ecosystems assets (encompassing renewable natural resources such as timber and fish) and non-renewable natural resources are clearly distinguished; (ii) that there is a balanced reflection of ecosystem service contributions in relation to both inputs and outputs; and (iii) supports accounting for the economy-wide effects of environmental pollution via either reduced flows of ecosystem services (as a result of the degradation of ecosystem assets) or through changes in measures of gross output or intermediate consumption (i.e. E, M and S).

The approach also has the benefit of providing a framing of connections to environmental stocks and flows that is exhaustive subject to data availability. That is to say that conceptually the set of ecosystem assets will cover an entire geographic territory in an analogous manner to a business register providing a complete coverage of economic units. Note that the set of economic units that constitutes an economy is defined by those units that are resident in a country and the associated geographic territory is consistent conceptually with that used to establish the set of ecosystem assets.[8]

Although the accounting basis for the ecosystem MFP model can be described clearly, it must be recalled that the growth accounting approach relies more fundamentally on production theory such that the difference between the growth in output and the growth in input can be legitimately interpreted as a measure of productivity. Of particular note is the relevance of assumptions concerning producer behaviour in terms of minimising costs or maximizing revenues. An important concern therefore is how the inclusion of ecosystem assets and ecosystem services may be linked to this production theory and associated assumptions.

While this issue definitively requires further research, two points are noted. First, a not unrelated issue arises in considering the inclusion of non-market production, for example of health and education services, in measures of economy-wide productivity. The discussion of relevant assumptions for this type of non-market activity may be more developed in part because there are definable economic agents involved but challenges remain.

Second, a possible way forward with respect to ecosystems is to consider that each ecosystem asset has an associated steward (analogous to the executive board of a company) that acts on behalf of the ecosystem

8 Accepting that in practice small differences may emerge, for example concerning territorial enclaves and embassies.

Table 1: Standard Supply and Use Table for Apple Farmer (currency units, e.g. dollars)

	Apple farmer	Other industries	Household final consumption	Total
Supply table				
Apples	800			800
Apple products		2000		2000
Fertilizer		200		200
Fuel		150		150
Total output (1)	800	2350		3350
Use table				
Apples		800		800
Apple products			2000	2000
Fertilizer	200			200
Fuel	150			150
Total input (2)	350	800	2000	3350
Gross value added (3=1-2)	450	1550	na	2000
Labour input: Wages and salaries (4)	150	600		750
Gross operating surplus (5=3-4)	300	950		1250

Source: Author's compilation

in making exchanges of ecosystem services with economic units. This framing might be considered implicit in the methods used in environmental economics to identify the willingness of economic units to pay for ecosystem services, and inherent in the design of environmental markets and related payments for ecosystem services schemes. To the author's knowledge these potential connections between ecosystems and production theory have not been developed.

Demonstrating the Ecosystem MFP Model

To demonstrate the links between ecosystem accounting and the Ecosystem MFP measure, the following stylized example is presented starting from the changes that would be reflected in the standard supply and use table entries for an apple farmer who utilizes pollination services. To provide a starting point for the example, Table 1 shows the entries in the standard supply and use table. No pollination services are recorded and there is simply crop outputs (in this case apples), and purchased intermediate inputs of fertilizer and fuel.

Incorporating "Direct" Ecosystem Services into MFP Calculations

The incorporation of ecosystem services into MFP calculations should be considered in a number of stages where different types of ecosystem services are progressively included. The most straightforward inclusion concerns ecosystem services where there is the direct use of an ecosystem by an eco-

Table 2: Extended Supply and Use Table for Apple Farmer for Direct Ecosystem Services (currency units, e.g. dollars)

	Apple farmer	Other industries	Ecosystem asset: Forest	Household final consumption	Total
Supply table					
Apples	800				800
Apple products		2000			2000
Fertilizer		200			200
Fuel		150			150
Ecosystem services: Pollination			200		200
Total output (1)	800	2350	200		3350
Use table					
Apples		800			800
Apple products				2000	2000
Fertilizer	200				200
Fuel	150				150
Ecosystem services: Pollination	200				200
Total input (2)	550	800	0	2000	3350
Gross value added (3=1-2)	250	1550	200	na	2000
Labour input: Wages and salaries (4)	150	600	0		750
Gross operating surplus (5=3-4)	100	950	200		1250

Source: Author's compilation

nomic unit. Using agriculture as a starting point, examples of ecosystem use include the abstraction of water for irrigation, the pollination of crops by wild pollinators, grass eaten by livestock and the absorption of soil nutrients in crop growth. For each of these types of ecosystem service there is an associated flow that reflects the flow of capital services that can be included in Ecosystem MFP formula.

In the example, in Table 2, the supply and use table is extended to record the imputed value of output of pollination services supplied by the neighbouring forest ecosystem and the use of those ecosystem services by the apple farmer. The result is that the value added that was previously attributed solely to the apple farmer is now partitioned across two producing units – the apple farmer and the forest ecosystem asset.

From an MFP perspective, we see that additional inputs (i.e. the pollination services) have been explicitly recorded in the production function of the apple farmer and can now be incorporated into the calculations.

In this example, the use of pollination services is recorded in a manner analogous to the leasing of machinery from a rental company. An alternative, but entirely consistent, recording might be considered if the ecosystem asset supplying the services was considered to be under the control of the apple farmer. This is implicitly the assumption in the OECD's EAMFP. In this case the flow of ecosystem services would not be recorded as a part of intermediate inputs but rather as a flow of capital services which would, in effect, be shown in a

Table 3: Extended Supply and Use Table for Apple Farmer for Direct and Indirect Ecosystem Services (currency units, e.g. dollars)

	Apple farmer	Other industries	Ecosystem asset: Forest	Household final consumption	Government final consumption	Total
Supply table						
Apples	800					800
Apple products		2000				2000
Fertilizer		200				200
Fuel		150				150
Ecosystem services: Pollination			200			200
Ecosystem services: Global climate regulation			250			250
Total output (1)	800	2350	450			3600
Use table						
Apples		800				800
Apple products				2000		2000
Fertilizer	200					200
Fuel	150					150
Ecosystem services: Pollination	200					200
Ecosystem services: Global climate regulation					250	250
Total input (2)	550	800	0	2000	250	3600
Gross value added (3=1-2)	250	1550	450	na		2250
Labour input: Wages and salaries (4)	150	600	0			750
Gross operating surplus (5=3-4)	100	950	450			1500

Source: Author's compilation

partitioning of the apple farmer's gross operating surplus, together with the capital services of any machinery and equipment for example.

The benefit of partitioning the ecosystem asset as a producing unit is that it facilitates both understanding inputs to the apple farmer but also the recording of other ecosystem services that may be supplied by the partitioned ecosystem asset, for instance global climate regulation services by the forest (Table 3). Allowing for multiple services and multiple beneficiaries in the measurement of MFP is core benefit of using the Ecosystem MFP approach.

Incorporating Broader Benefits Arising from Agricultural Land

As just introduced, a third stage of potential extension is recognizing that there will be a range of positive externalities that could be considered in understanding the full production function and relevant trade-offs. Thus, the incorporation of ecosystem services can be extended to include, for example:

- The global climate regulation services (via carbon sequestration and retention) of ecosystems which provide benefits globally,
- The role that ecosystems play in the regulation of water flows within a water catchment and
- The cultural benefits obtained from the good management of landscapes.

Table 3 incorporates just one additional ecosystem service, global climate regulation services, thus adding rows to the supply and use tables and recording supply by forest ecosystems and use by general government (following the convention for recording the use of these services in the SEEA Ecosystem Accounting). Note that total gross output and total value added of the system as a whole are increased through this addition since the production and. consumption of global climate regulation services concerns output that is outside the SNA production boundary.

From an MFP perspective, this extension has no effect on aggregate MFP since both outputs and inputs are increased equally. However, this extension does allow a richer understanding of the role of natural capital to be reflected, in this case for forest ecosystems. For this extension and the previous extension concerning pollination services, the incorporation into measures of MFP will require estimation of volume indexes showing the growth in ecosystem services together with estimates in nominal terms (as presented in Tables 2 and 3) to provide weights for the derivation of combined output and combined input measures.

Incorporating the Effects of Environmental "Bads"

A fourth stage in the incorporation of ecosystem services is facilitating analysis of the effects of environmental "bads" as undertaken in a number of approaches to EAMFP. Notwithstanding the accounting concerns raised in the previous section, it is noted that one motivation for the deduction of bads from output is that the negative effect is attributed directly to the polluter – in effect it is a polluter pays framing of the analysis. From an accounting perspective however, the effects of negative external events are not treated in this way, unless of course the pollution affects the polluter. Put differently, accounts record the first round, direct implications of external effects on stocks and flows across all economic units and, in the context of ecosystem accounting, all ecosystem assets. What is not undertaken is any attribution of blame for those changes in stocks and flows, i.e. accounting does not directly provide a polluter pays perspective. When considered from the perspective of economy-wide measures of MFP, it is likely that in most cases of air and water pollution there will be the scope for all of the effects in terms of increased costs or reduced revenues to be captured, even when not attributed to a causing unit.

This capacity of an economy wide MFP measure to capture a full range of negative external effects is reinforced through the extension to record ecosystem services since many of the effects of pollution will relate to loss in environmental quality and the subsequent loss of ecosystem services contributions. For example, pollution of water bodies may lead to water supply companies spending more on water treatment to support the water purification services received from ecosystems. Thus, from the perspective of economic units affected by environmental bads, the Ecosystem MFP will provide a direct and more encompassing measure of the changes in their productivity as a result of pollution. At the same time, since a measure of industry productivity based on a polluter pays framing may be relevant in some contexts, additional analysis and reorganization of data will be required that is beyond the Ecosystem MFP framing.

Research Challenges and Future Directions

Overall, the incorporation of ecosystem services into the derivation of MFP should support a more extensive analysis of economy wide productivity. In particular, it is highlighted that there is the potential to reflect, in the measures of MFP, the results of investments in ecosystem management and restoration – for example via nature-based solutions - as part of the productivity equation both in the context of measuring industry outputs and in the broader benefits that positive ecosystem management can provide.

There are two key challenges in incorporating ecosystem services. First, there is challenge of understanding and measuring the relationship between the physical flows of ecosystem services and the associated outputs. Commonly, there are no simple linear relationships involved with the supply of ecosystem services. The flows will be dependent on a range of factors including the relative condition of the ecosystem asset (and neighbouring assets), and the extent to which produced inputs are used, for example the application of fertilizer and pesticides or the supply of infrastructure to support recreation in national parks. However, while the precise articulation of the link between ecosystem services and output may be difficult to measure, this challenge also arises for produced capital (although perhaps to a lesser extent) whereby assumptions about the link between assets and capital service flows are made following generalized models (OECD, 2001).

The second challenge lies in estimating the cost share relevant for these inputs. Where ecosystem services flow directly into the production of outputs that are included in standard measures of industry value added, in concept the value of the ecosystem service inputs should be incorporated implicitly in estimates of gross operating surplus, i.e. the total non-labour share is unchanged. In these cases it is a matter of partitioning the gross operating surplus between the return to produced capital and the return to ecosystem assets. This is akin to the measurement of resource rent as applied in standard natural resource accounting and also to the valuation of ecosystem services via production function methods (Freeman *et al.*, 2014). However, for other ecosystem services a range of non-market valuation techniques will likely need to be applied as introduced in the SEEA Ecosystem Accounting (Chapter 9).

Beyond these ecosystem measurement challenges, a much more detailed mathematical representation of the Ecosystem MFP model is needed building on the logic presented in equation (7). In particular, it will be necessary to take the ecosystem accounting concepts and blend them with the standard capital and growth accounting theory and related index number approaches. An important aspect in this work will be understanding the alignment between ecosystem accounting and the production and consumption theory that underpins growth accounting. It is likely that research in this area will have related benefits in the ongoing research to develop valuation techniques for ecosystem services that are required for national accounting uses. Steps in this direction are evident in the work of Fenichel *et al.* (forthcoming) but more research and discussion is needed.

Also, research is needed on the appropriate accounting for actions taken by economic units to restore or enhance ecosystems. These actions will involve incurring labour, capital and intermediate input costs. But at present there is no additional output recorded in the national accounts and the connections to changes in the future flows of ecosystem services have not been well developed. A potential approach is to consider these costs as investments and, following standard national accounts practice, this would lead to increases in produced capital albeit that these investments are embodied in ecosystem assets. Appropriately disentangling the produced and natural capital elements and accounting appropriately for renewable assets is an important area for investigation.

In relation to implementation there are many areas of potential work. The implementation of ecosystem accounting is progressing and there are a wide range of landscape, national and regional projects underway but a single database containing the relevant inputs for calculation of the Ecosystem MFP measure has not been established. Experience to date suggests that progress on ecosystem accounting will generally involve bringing together a wide range of existing data. There would appear to be great potential to examine data that currently underpins the variety of environmental-economic models that have been developed that incorporate information on physical and ecological flows in conjunction with economic data. Integrating these data within an accounting framework will be an important step.

The most challenging area of measurement is likely to be the valuation of ecosystem services such that relevant cost shares within the accounting framework can be determined. Given that ecosystem services are not exchanged on markets, it will be important to advance the testing and implementation of appropriate non-market valuation techniques. One option that has emerged in the research for this article is the use of Malmquist indexes and distance functions which have been considered in EAMFP measurement but not, to the authors knowledge, applied in the context of valuing ecosystem services.

Overall, while these are challenging research tasks, the broadening of the MFP framework to incorporate environmental adjustments using ecosystem accounting provides an excellent platform for undertaking an integrated research program that can utilize findings from many different areas of work.

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

Christina Caron[1]

Abstract

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

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

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

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

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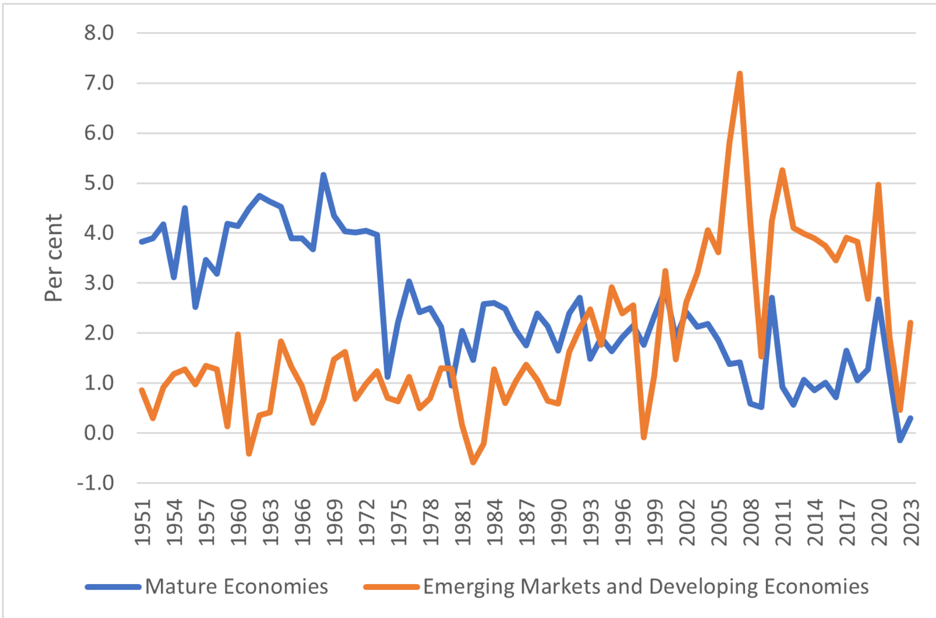
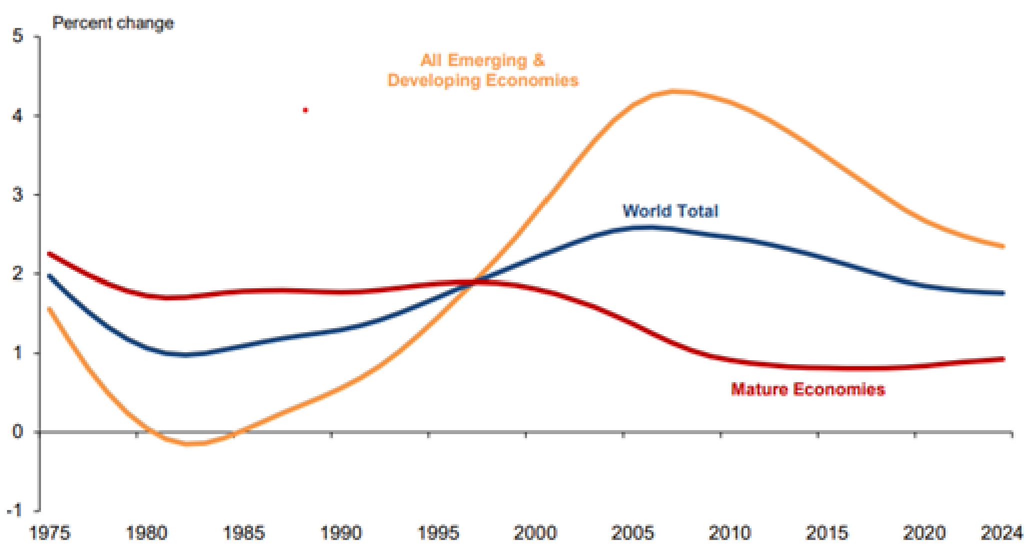
Chart 1: Hourly Labour Productivity in Mature and Emerging Market and Developing Economies, 1951-2023 (annual per cent change)



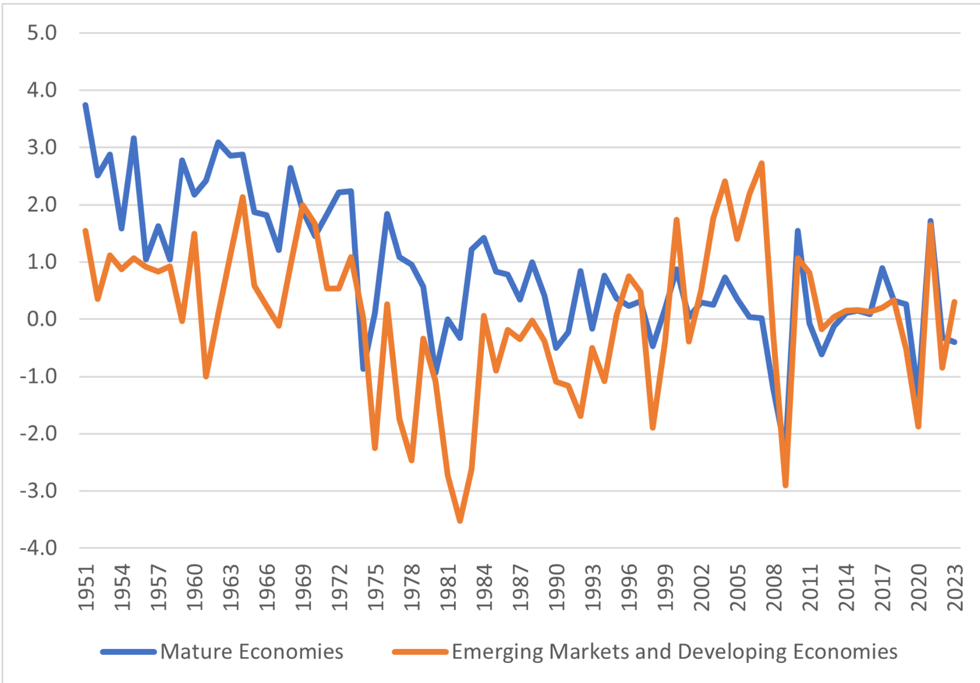
Source: The Conference Board Total Economy Database (TED)

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



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

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



Source: The Conference Board Total Economy Database

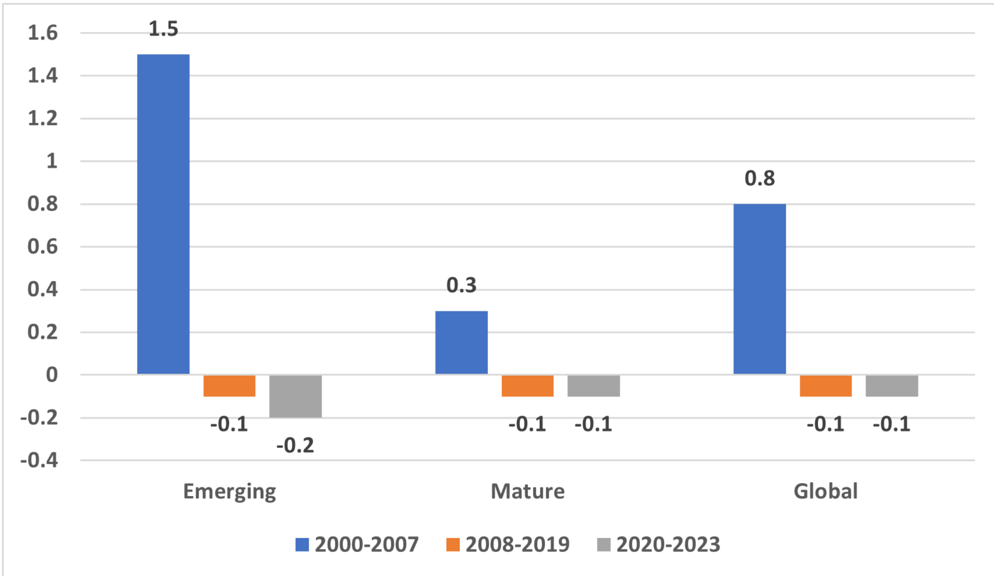
In advanced economies, while there have been periodic surges – such as the US turn-of-the-century bounce widely attributed to the impact of the information and communication technology (ICT) revolution, and the rebound following the 2008-09 global recession – the underlying MFP/Total Factor Productivity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

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

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

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

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



Source: The Conference Board Total Economy Database (2024)

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

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

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

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

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

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

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

Natural Capital and Its Link to Productivity

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

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

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

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

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

Natural Capital: From Productivity Driver to Productivity Depressor

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

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

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

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

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

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

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

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

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

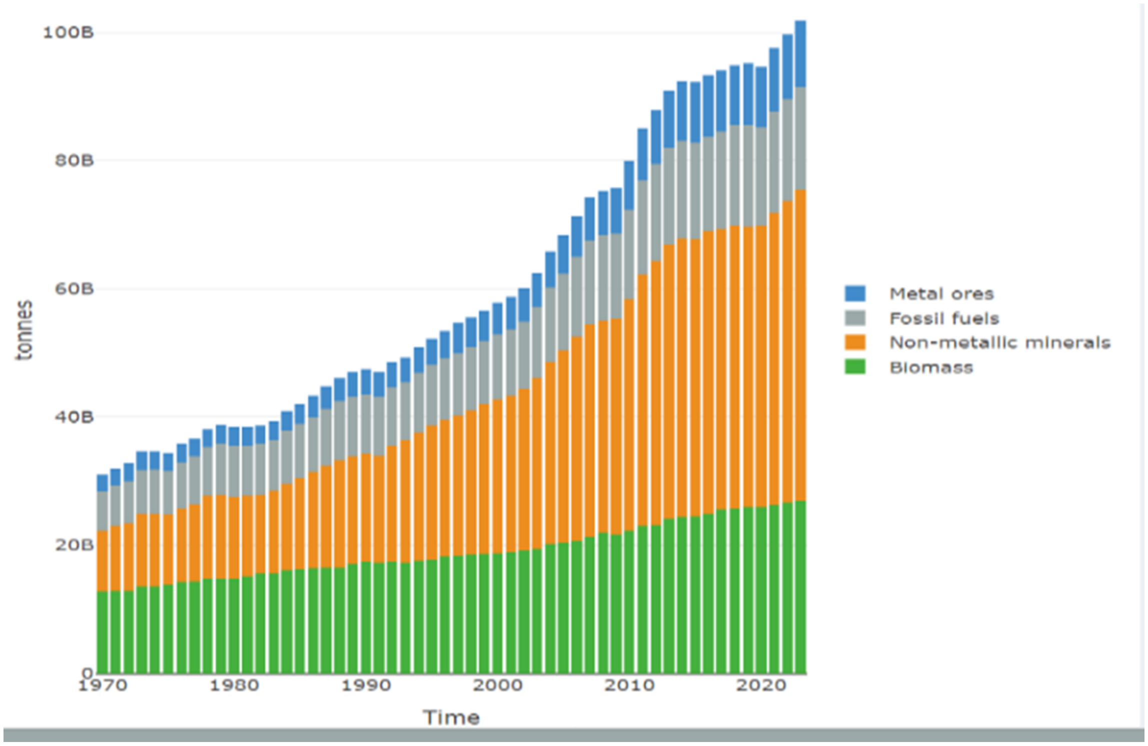
6 This transition was described by Kenneth Boulding, who used the terms 'cowboy economy' and 'spaceman economy' (Boulding, 1973).

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

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

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

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



Source: Vienna University (2024)

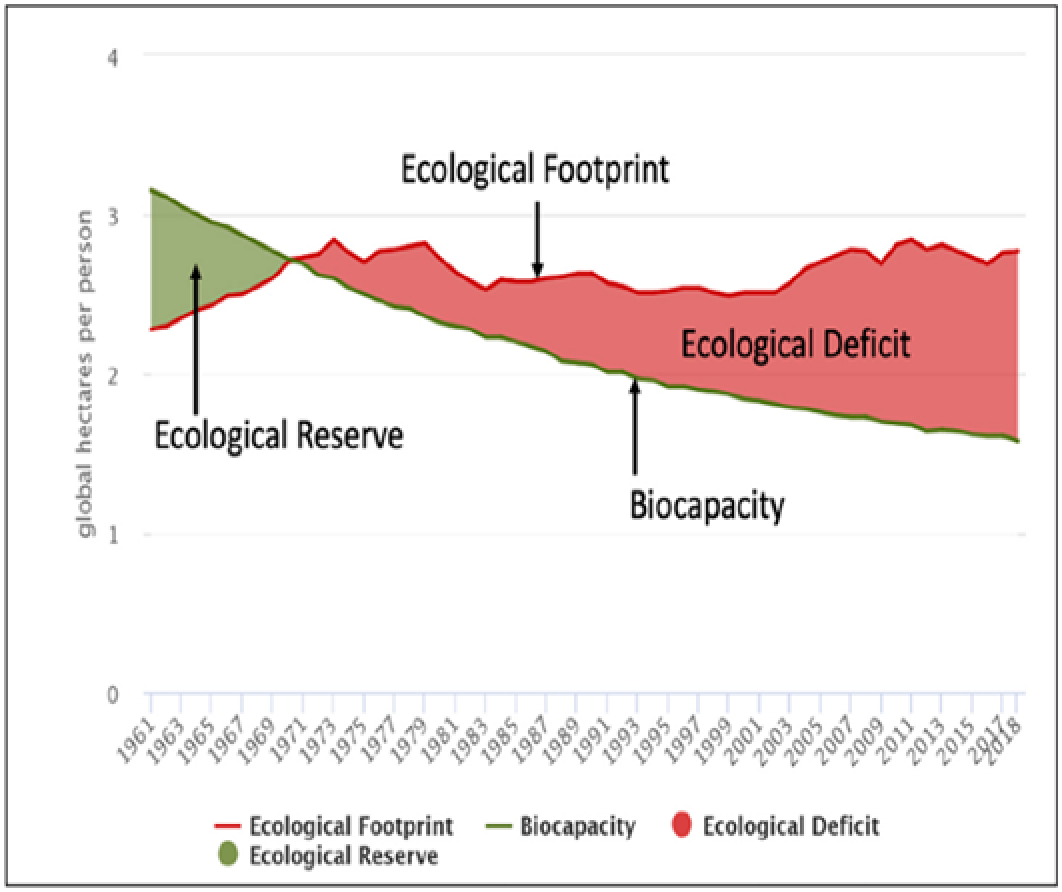
fifty-fold (Steffen *et al.*, 2008).

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

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

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

Chart 6: Global Ecological Footprint and Biocapacity per Capita



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

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

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

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

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

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

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

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

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

Measured Declines in Natural Capital

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

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

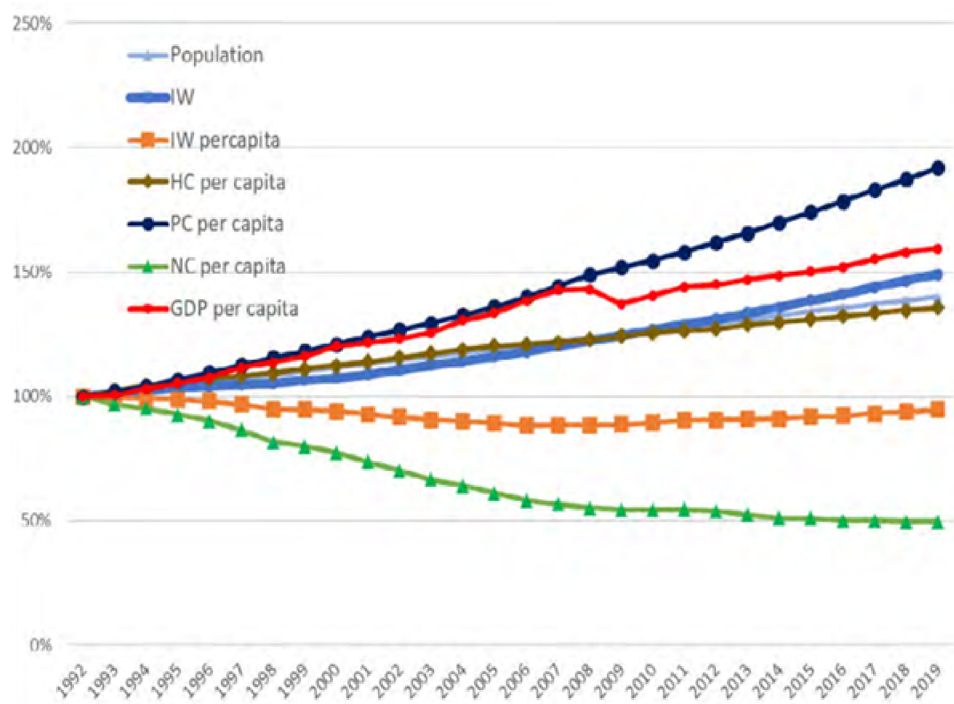
The value of natural assets is defined by the UNEP as the present discounted value of the future net benefits that can be expected over the life of the resource, based on a discount rate of 5 per cent. Thus the assessed value of forests, for example, goes well beyond timber values and also includes the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

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

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

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

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



Source: UNEP (2023)

used. [14]

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

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

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

these calculations (Tol, 2023).

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

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

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

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

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

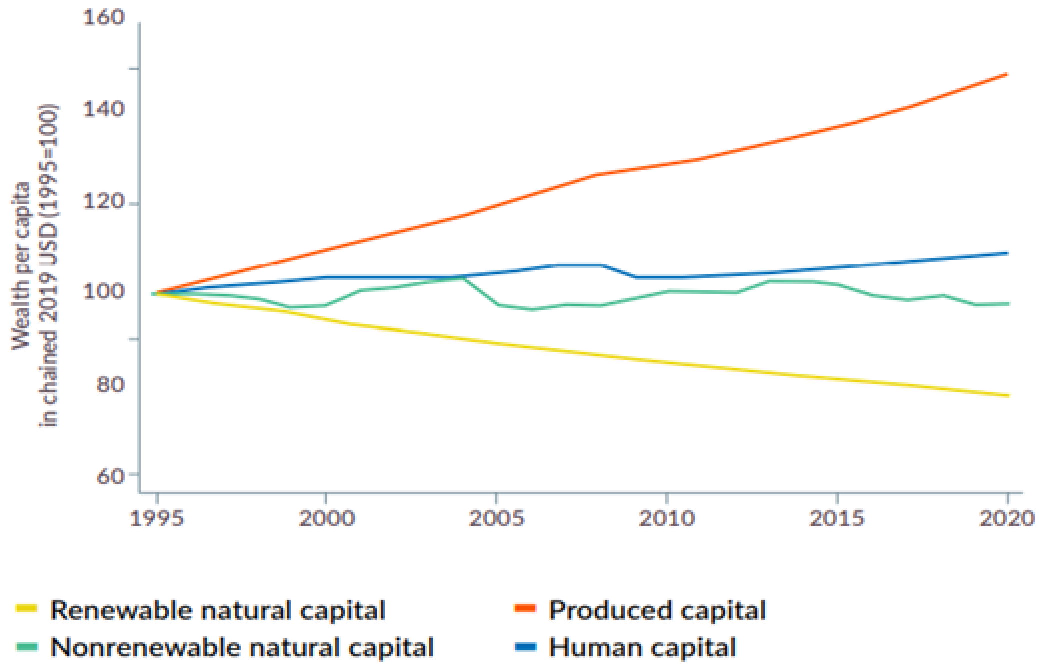
The World Bank, like the UNEP, finds significant declines in global natural capital per capita over the assessed time period. Chart 8 shows the World Bank assessments that between 1995 and 2020 on a per capita basis: global produced capital rose by 47 per cent; human capital rose by 9 per cent; nonrenewable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

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

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

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

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



Source: World Bank (2024)

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

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

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

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

Impacts of Declining Natural Capital on Productivity

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

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

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

Insights from the Literature

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

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

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

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

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

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

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

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

GDP growth = PK contribution + L contribution + MFP

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

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

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

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

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

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

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

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

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

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

Scientific Evidence on the Deterioration of Natural Capital

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

Climate Change

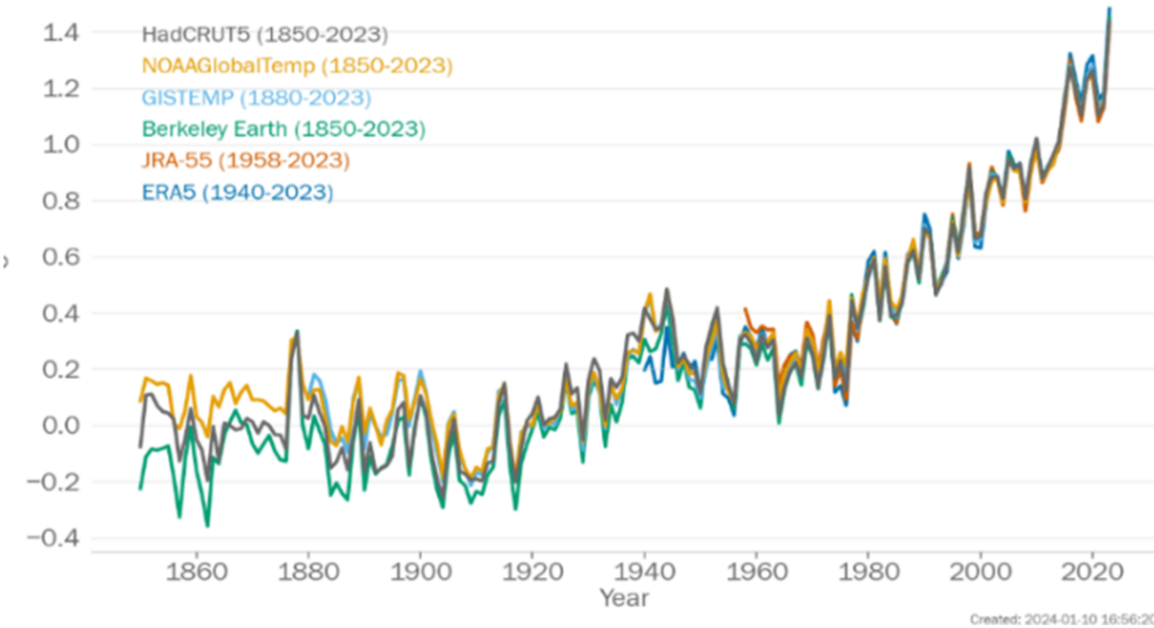
Atmospheric concentrations of greenhouse gases have reached their highest levels in two million years, driving accelerating manifestations of climate change (IPCC, 2023). By 2023, global air temperatures had risen to nearly 1.5° C above pre-industrial levels – the preferred upper limit under the Paris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

Rising air and ocean temperatures have

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

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

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



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

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

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

Biodiversity Loss

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

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

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

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

Soil and Sub-soil Resource Depletion

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

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

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

Waste, Pollution and Contamination

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

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

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

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

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

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

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

Natural Capital and Productivity: the Evidence

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

Climate Change

Macroeconomic Effects

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Extreme Weather Events

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

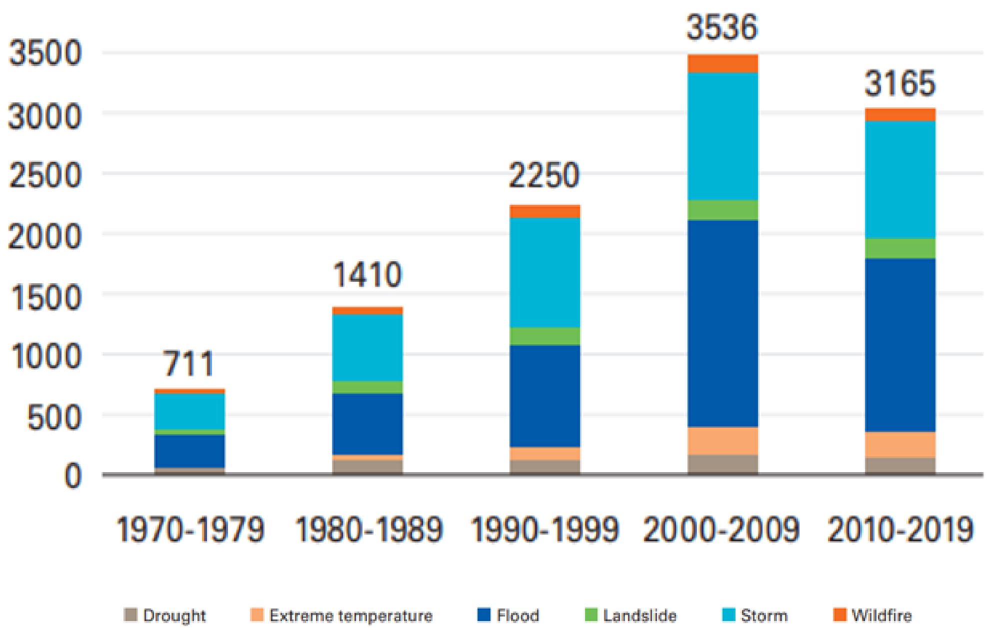
Such events – representing progressive loss of the ecosystem service of climate stability – are among the most costly forms of natural capital depletion in terms of output and productivity impacts, but are typically not included in Integrated Assessment Models (Newman and Noy, 2023).[27] Globally, they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

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

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

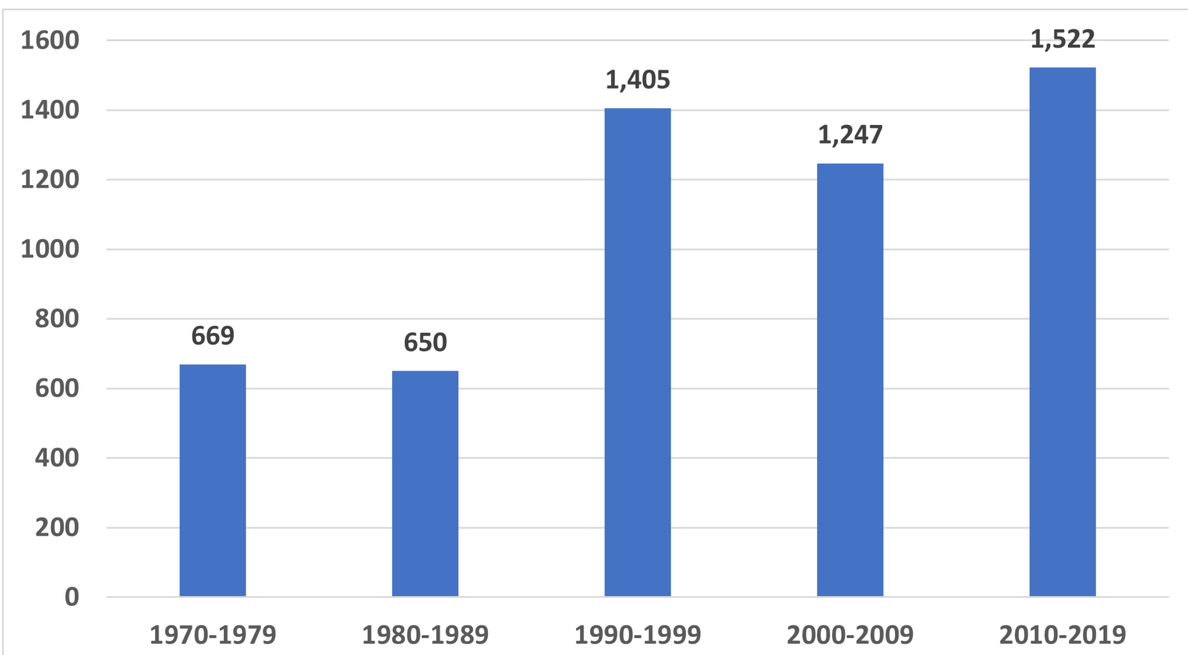
27 Integrated Assessment Models are models that incorporate both scientific and economic data in order to evaluate the nature and magnitude of environment-economy interactions.

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



Source: WMO (2021)

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



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

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

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

Labour Productivity and Human Capital

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

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

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

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

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

Sectoral effects

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

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

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

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

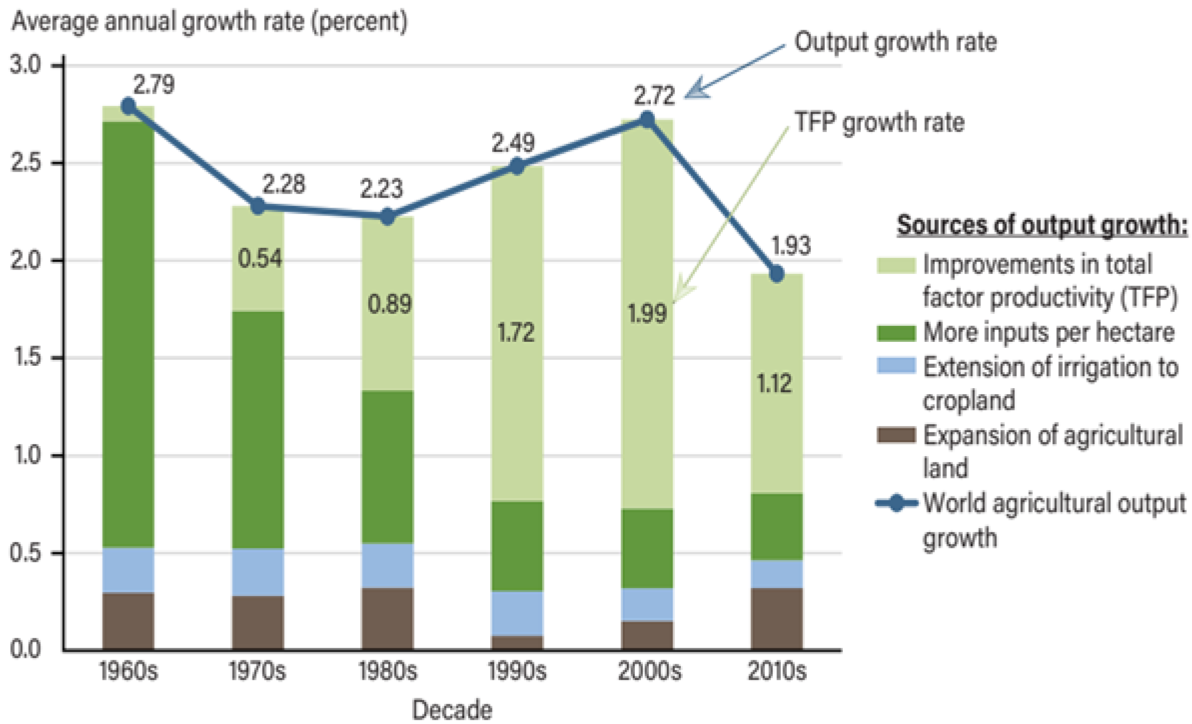
The Food and Agriculture Organization (FAO) found that disaster events reduced global agricultural GDP by growing amounts between 1972 and 2022, averaging 5 per cent over the entire period; this constituted an annual drag of 0.2 per cent of global GDP (FAO, 2023).

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

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

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

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



Source: Fuglie *et al.*, 2024

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

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

Dynamic Effects

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

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

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

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

Impacts of Deterioration of Nature on Productivity

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

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

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

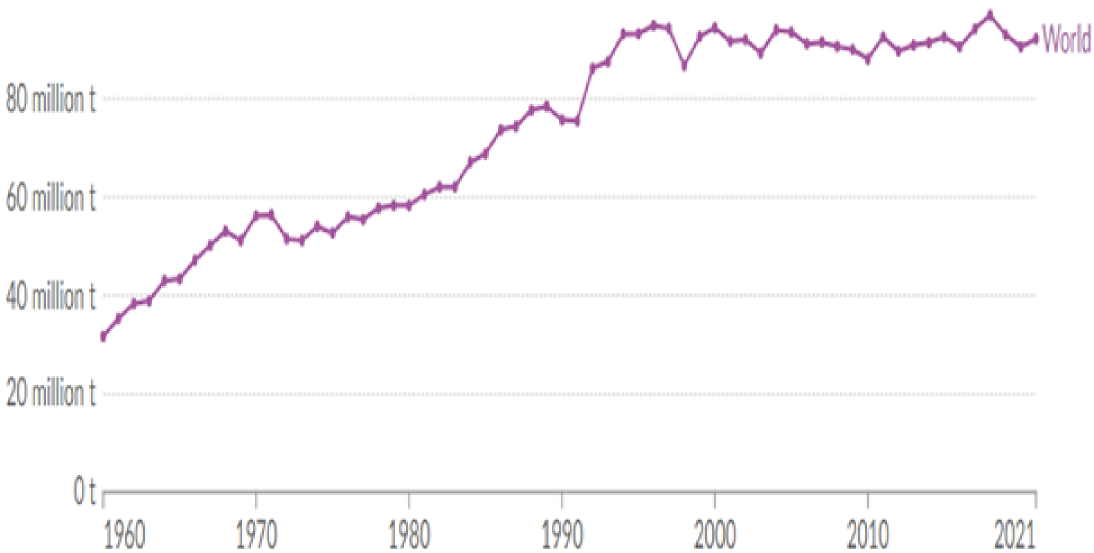
Depleted Fish Populations

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

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

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

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



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

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

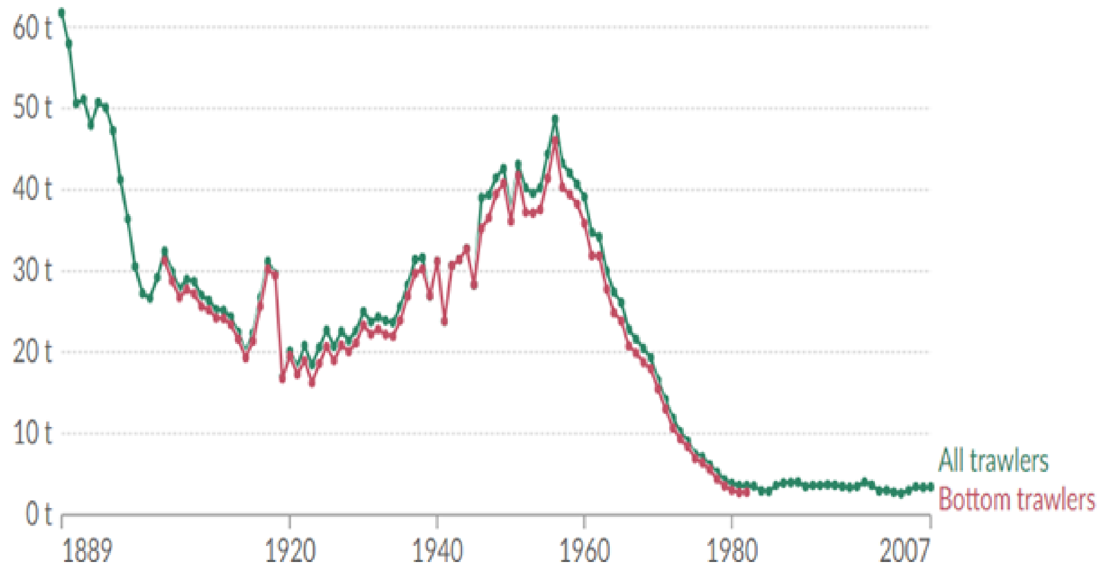
The asset value of global wild capture fisheries collapsed by 83 per cent between 1995 and 2018 due to depletion of fish stocks (World Bank, 2021). While farmed fish production has grown as marine catches have stagnated or fallen, it is an imperfect substitute. In addition to raising sustainability and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

Declining Wild Pollinator Populations

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

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

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



Source: Thurstan *et al.* (2010)

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

Declining Vertebrate Populations

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

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

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

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

Groundwater Depletion

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

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

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

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

Soil Degradation, Erosion and Contamination

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

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

Depletion of Mining and Oil and Gas Reserves

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

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

Productivity Impacts: Pollution

Air pollution

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

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

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

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

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

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

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

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

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

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

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

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

Summary and Conclusions

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

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

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

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

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

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