Emissions-Adjusted Total Factor Productivity*

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Abstract

Traditional estimates of total factor productivity (TFP) measure the output that a bundle of inputs produces. But production comes with emissions that stay in the atmosphere for decades, which means that productivity does not capture the full effect of today's production on the present value of consumption. We propose a measure for emissions-adjusted total factor productivity (TFPE) that takes these long-run effects into account. TFPE is a welfare-relevant measure of productivity under general assumptions consistent with canonical integrated assessment models and "green national accounts." It is straightforward to calculate and relies only on publicly available data, as well as an estimate of the social cost of carbon. TFPE alters recent productivity dynamics under high-end estimates of the cost of carbon and when global damages are internalized, attenuating or even reversing the post-2005 productivity growth slowdown in some economies, including in the United States. However, under conventional estimates of the social cost of carbon of $50 to $250, or when only domestic damages are considered, productivity trends are largely unchanged.

Keywords: Measurement, Productivity, Emissions, Climate, Growth

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1. Introduction

Productivity growth—improvements in the efficiency with which the economy transforms inputs into aggregate output—is the main driver of long-run increases in living standards (Jones 2016). It therefore concerns economists and policymakers alike that productivity growth in advanced economies has been weak for the past two decades (Goldin et al. 2024, Fernald et al. 2025). In the United States, for example, productivity growth has averaged just 0.6% since 2005, far below its historical average of 1.5% (Figure 1a). The slowdown is even more pronounced in Europe, where several countries have experienced outright productivity declines (Draghi 2024).

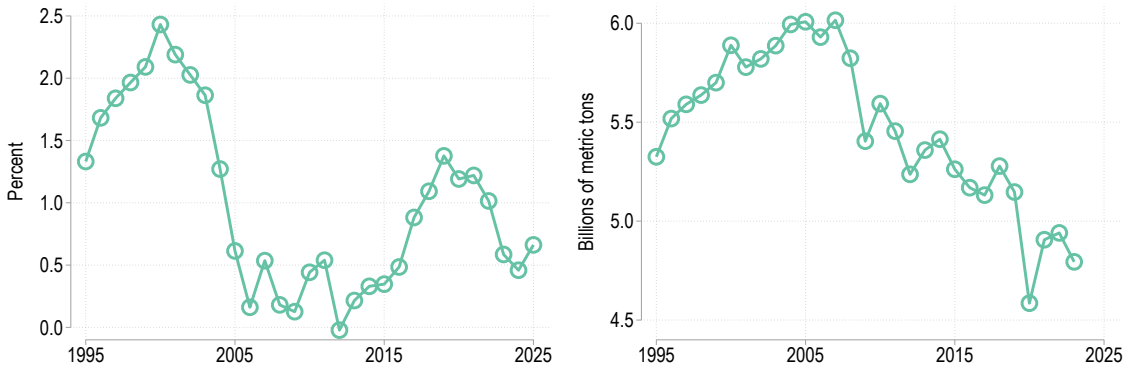
But do these productivity statistics capture the full extent to which economic efficiency is improving? Economists have long recognized that measures of economic activity are welfare-relevant only if they account for all changes in future consumption possibilities induced by today's production decisions (e.g. Weitzman 1976). Standard productivity statistics do not fully do so. Perhaps the most glaring omission is carbon dioxide emissions, which affect both the climate and future economic activity (e.g. Nordhaus 1977, Hassler et al. 2016, Nath et al. 2024, Bilal and Stock 2025, Bilal and Känzig 2026). The omission is particularly relevant today, as carbon dioxide emissions have been *falling* in many advanced economies: U.S. emissions are now 23% below their peak (Figure 1b; Aghion et al. 2025). An economy that reduces emissions while maintaining output reduces climate-related damage and thereby expands future consumption possibilities. Productivity statistics are therefore welfare-relevant only if they account for such changes in the emissions intensity of production. How can productivity be adjusted for changes in emissions? And does such an adjustment meaningfully change the path of productivity growth?

This paper quantifies the path of the welfare-relevant measure of productivity in an economy with emissions and establishes the conditions under which emissions alter productivity dynamics. Emissions-adjusted total factor productivity (TFPE) is the marginal effect of an increase in input use on the present value of the consumption path, taking into account the damage that today's emissions impose on future consumption. Measuring efficiency with TFPE restores the link between welfare and productivity in a general framework that nests canonical integrated assessment models (e.g., Nordhaus 1992, Golosov et al. 2014). TFPE also coincides with the Solow residual of green GDP—a central concept in the literature on green national accounts (e.g., Dasgupta 2009, Muller et al. 2011)—while remaining a welfare-relevant measure of efficiency under weaker assumptions than green GDP.

It may seem unconventional to define productivity as a forward-looking variable that measures the effect of today's production on future consumption. However, this is also a feature of TFP measures such as the Solow residual, as output is used both for consumption and investment. Weitzman (1976) shows that if investment goods are competitively priced, net investment encodes the present value of future consumption that results from it. This makes productivity statistics that capture the rate at which inputs generate net output forward-looking: they capture the effect of inputs on future consumption.[1] TFPE thus generalizes TFP, and coincides with it in the absence of emissions.

[1] We should note that, in practice, productivity is measured as the rate at which input bundles produce gross rather than net output, and that Weitzman (1976) imposes additional assumptions on technology and interest rates. Generalizations of the original Weitzman result are provided in Weitzman and Löfgren (1997) and Weitzman (1998).

Figure 1. Trends in U.S. Total Factor Productivity Growth and Carbon Emissions



(a) Productivity Growth (b) Carbon Emissions

Notes: The left-hand figure plots the 5-year moving average of productivity growth, adjusted for capital utilization using the series from Fernald (2014). The right-hand figure plots carbon dioxide emissions in billions of metric tons.

TFPE is straightforward to calculate. It only requires publicly available data on carbon dioxide emissions, GDP, traditionally measured TFP, and an estimate of the social cost of carbon. The latter is defined as the marginal effect of emissions on the present value of consumption and is frequently estimated in the data because it determines the optimal Pigouvian carbon tax (Hassler and Krusell 2018). In the calculations that follow, the social cost of carbon therefore plays the role of a sufficient statistic in the sense of Chetty (2009): it condenses into a single number all assumptions and forecasts about the channels through which emissions affect the path of consumption, how long these damages persist, and how future consumption is discounted. Assumptions about the cost of carbon also embed the extent (if any) to which society internalizes global damages from its emissions.

The literature has by no means converged on a definitive social cost of carbon, as estimates rely on both different assumptions and empirical methods. Most estimates, taking global damages into account, range between $50 and $300 per metric ton of carbon dioxide in 2017 dollars.[2] At the top end of estimates, Bilal and Känzig (2026) derive a $938 cost of carbon in 2017 dollars from a time series regression of global temperature shocks on global output. In a meta analysis allowing for broader damages beyond economic activity, Moore et al. (2024) finds a $252 average. U.S. federal policy assumed a $48 social cost in 2021, which rose to $180 by 2023 (Carleton and Greenstone 2022).

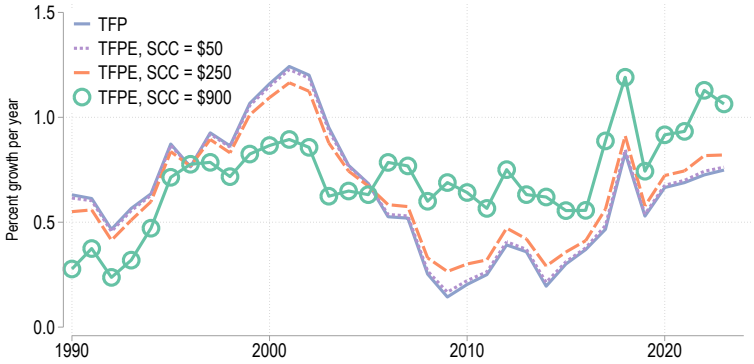
In all but the largest economies, domestic-only damages are an order of magnitude smaller than the social (i.e. global) cost of carbon, and may even be negative in colder economies that benefit from rising temperatures, such as Canada and Scandinavia (Nath et al. 2024). U.S. climate policy adopted an exclusive focus on domestic costs between 2017 and 2021, for example, which implied that emissions were evaluated at a cost of less than $8 per ton (Voosen 2021).

Given the dispersion in the estimates, we take an agnostic approach and calculate TFPE for a range of values of the cost of carbon: $50, $250, and $900.[3] For the purpose of calculating productiv-

[2] To illustrate, the carbon dioxide emissions related to an Economy-class seat on a direct flight from London to Boston equal around 250kg. At a social cost of carbon of (say) $300 per metric ton, a ticket's optimal Pigouvian tax equals $75.

[3] These are the values that we use for the social cost of carbon in 2017, measured in 2017 dollars. We allow these costs to grow at 2.1% per year in real terms to reflect rising damages over time. Section 3.1 elaborates.

Figure 2. TFP and TFPE growth in the United States



Notes: The figure plots five-year centered moving averages of TFP and TFPE growth for the United States. TFP growth is computed from the real TFP index at constant national prices in Penn World Table 11.0.

ity it does not matter whether these social costs differ because of scope (e.g. whether one internalizes the global damages induced by domestic emissions or not) or differences in the estimated intensity of damages (e.g. because of the econometric technique deployed). This comes from the fact that TFPE is the productivity index of an economy with emissions at any cost of carbon: it provides a mapping from climate damages into productivity, allowing productivity dynamics to be evaluated consistently across a wide range of views about the magnitude and scope of damages. The three values we consider are helpful in that they allow us to illustrate whether and how productivity dynamics change as a result of the observed changes in emission intensity.

Figure 2 previews our main results, focusing on the United States. It plots the path of traditionally-measured TFP against the paths of TFPE for the range of costs of carbon.[4] At a social cost of carbon of $50 per metric ton, TFPE is hard to distinguish from TFP. At those costs, adjusting the level of productivity for emissions lowers its level by less than 1%, so the effect on productivity growth is near zero. This has a natural interpretation: at those levels of the cost of carbon, the implied welfare effects of climate damages are negligible relative to the welfare effects of typical variations in productivity growth. Qualitatively, the same conclusion holds for the cost of carbon of $250: namely, the adjustment for emissions is small relative to the usual volatility of measured TFP.

At higher values of the cost of carbon, TFPE and TFP growth rates are meaningfully different. At a cost of carbon of $900, for example, TFPE growth in the U.S. has steadily increased — rather than slowed — over the past two decades. The gap between the levels of TFP and TFPE, which captures the scope for future excess productivity growth from reducing emissions to zero, is 27% in 2025.

Thus, adjusting for emissions can materially affect both the level of productivity and the dynamics of productivity growth, but only at social costs of carbon near the very upper end of the literature, such as those estimated by Bilal and Känzig (2026). At more conventional values, the benefits from avoiding climate damages are small relative to modest improvements in traditional productivity growth. Policymakers relying on such costs of carbon in cost–benefit analyses would struggle to justify prioritizing climate policy over conventional growth-enhancing policies.

[4] We compute TFPE for most economies globally in the main body of the paper, as well as for the world as a whole.

Related Literature. This paper is most closely related to the literature on adjusting national accounts for environmental externalities, and on the welfare relevance of total factor productivity. The "green national accounts" literature builds on the insight in Weitzman (1976) that, under particular conditions, aggregate output net of capital depreciation equals the present value of consumption that households will derive from today's output.[5] If future consumption is affected by carbon in the atmosphere, carbon emissions amount to a depreciation of natural capital, and those damages should be subtracted from gross domestic output in order to measure welfare. Nordhaus (2021) summarizes this idea, labeling aggregate output net of environmental depreciation "green national income". This is part of a long literature with early contributions including Solow (1986), Hartwick (1990), and Weitzman and Löfgren (1997).[6]

Our approach is complementary to, but distinct from, this literature. It is complementary in the sense that TFPE coincides with the Solow residual of green output, so it is the relevant productivity concept for decomposing the growth of green national accounts. As noted by Basu and Fernald (2001), productivity is generally a first-order measure of welfare because, in contrast to measures of aggregate output, it quantifies the economy's ability to produce consumption goods *net of the opportunity costs* of inputs. It is distinct in the sense that TFPE is welfare-relevant under weaker assumptions. The welfare interpretation of green GDP is a level result: it requires the conditions under which an entire path of net output, valued at correct accounting prices for produced and natural capital, can be aggregated into the annuity-equivalent value of welfare. By contrast, TFPE is a marginal object. Because it measures the effect of an additional bundle of inputs on welfare, it can be derived from the envelope condition, requiring only the relevant marginal accounting prices—in particular, correct prices for investment goods—rather than the stronger regularity conditions needed for the full integral of output to be welfare relevant as in Weitzman (1976).

A related strand of research seeks to adjust GDP or productivity growth for environmental factors treating the environment as a production *input*. Notably, the OECD has estimated Environment-Adjusted Total Factor Productivity for 1996-2018 (Rodríguez et al. 2018, 2023).[7] While we share the high-level motivation of constructing economic aggregates that account for environmental damage, our approach is different.[8] The OECD's measure addresses the question: what would the growth of GDP or TFP be at each point in time if environmental damage had remained unchanged since the last period? This differs from our proposal in a number of ways. Primarily, TFPE is a welfare-relevant index of productivity: it captures the economy's ability to convert inputs into (the present value of) consumption, taking the long shadow of emissions on future output into account. The OECD's metric, in contrast, is static. Additionally, the OECD's measure treats emissions as a production input, and relies on constant emissions output elasticity estimates across the sample period. Besides the

[5] Formally, Weitzman shows that a constant consumption path equal to the current net national output delivers the same welfare as the equilibrium consumption path. We review Weitzman's insight in Supplementary Appendix A.

[6] Muller et al. (2011), for example, quantify such accounts for the U.S.

[7] Agarwala and Martin (2022) provide similar calculations for the United Kingdom. Xia and Xu (2020) perform a similar exercise to measure "green TFP" across Chinese provinces, using a non-parametric method from operations research to measure production efficiency. Their method is conceptually different from ours, and the authors find that green TFP in China has grown faster than TFP. That is the opposite of what we find for TFPE.

[8] The correlation between TFPE growth and that of the OECD's measure for the overlapping sample is 0.38.

complexity of estimating that elasticity in the presence of measurement error, this approach may be sensitive to changes in the output elasticity over time, such as those driven by green innovation. Instead, TFPE treats pollution as a byproduct of production, and only requires data on traditionally-measured productivity growth, emissions, GDP and an estimate of the social cost of carbon. Finally, a potential drawback of these calculations is that marginal elasticities are used to estimate the effects of potentially infra-marginal changes in emissions. Our methodology uses insights from the green accounting theory to bypass this difficulty.[9]

More broadly, we build on the literature that incorporates climate damages into the analysis of macroeconomic growth. A detailed review is provided in Nordhaus and Boyer (2003) and Hassler and Krusell (2018). Examples of recent influential contributions include Golosov et al. (2014), who provide a modern general equilibrium model to analyze optimal carbon taxation.[10] We also relate to the literature that emphasizes interactions between climate change and endogenous growth (Acemoglu et al. 2012, Acemoglu et al. 2016).[11] Our contribution is to provide an easily measurable productivity metric, consistent with the canonical models of macroeconomics and climate.

Our finding of a gradual acceleration in U.S. TFPE growth offers a more optimistic perspective on recent productivity trends. Adler et al. (2017) show that productivity growth has fallen since the mid-2000s in most advanced economies. A review of the literature on the slowdown's drivers is provided in Goldin et al. (2024) and Fernald et al. (2025). We show that when lower carbon emissions are taken into account, the slowdown is milder and, for high costs of carbon, in some cases reversed.[12] Conversely, we find that if the social cost of carbon is closer to the previous consensus, then the economic fallout from climate change is small relative to the benefits of slightly higher productivity.

While we only consider the economic costs of climate damage, the exercise is related in spirit to recent work that broadens the welfare relevance of key macroeconomic indicators. Jones and Klenow (2016) propose a summary statistic for economic well-being that goes beyond GDP by including leisure, life expectancy and inequality. Adhami et al. (2024) compare growth in welfare across countries taking into account both consumption per capita and population growth. Basu et al. (2022) derive the conditions under which productivity and capital capture the present value of consumption. Maideu-Morera (2024) shows that technological change has raised living standards by making work safer and more enjoyable, though the slowdown of productivity growth since 2005 is worse when job amenities are taken into account. Relatedly, Rachel (2021) shows that an increase in leisure-enhancing technological progress reduces growth in traditional TFP measures.

[9] The social cost of carbon estimates that we use also rely on marginal elasticities, but these marginal prices deliver welfare-relevant national accounts, as Weitzman (1976) points out. We show that this is also the case for productivity.

[10] A related literature studies the effect of depletion of exhaustible resources on growth. Dasgupta and Heal (1974) is an early model of non-renewable resources; Stokey (1998) formalizes how non-renewables may create bounds on growth.

[11] Early contributions in this field include Bovenberg and Smulders (1995) and Bovenberg and Smulders (1996). Empirical evidence of path dependence is provided in Aghion et al. (2016). A detailed review of the literature on directed technological change, with an emphasis on the environment, is provided in Aghion et al. (2019), Hémous and Olsen (2021) and Dechezleprêtre and Hémous (2022). Hassler et al. (2021) note that directed technological change has limited short-term effects because of the low elasticities of substitution between polluting and non-polluting industries. Aghion et al. (2025) present an endogenous growth model with non-homothetic preferences to show that productivity growth can fall when emissions decline, because national accounts inadequately adjust price indices for quality improvements.

[12] TFPE also ensures that welfare benefits of renewables (e.g., Arkolakis and Walsh 2023) are captured by productivity.

Outline The remainder of the paper proceeds as follows. We present the framework in Section 2. Data sources are detailed in Section 3, while the TFPE series are presented and analyzed in Section 4. Section 5 concludes.

2. Framework

We examine productivity in an economy where economic activity comes with emissions. The framework nests standard integrated assessment models (e.g. Nordhaus 1992, Golosov et al. 2014). We start by considering a global economy and discuss how the welfare-relevant productivity measure differs from TFP. Finally, we turn to productivity measurement at the country level, given the fact that global emissions affect domestic households and domestic emissions affect households abroad.

2.1. Economic environment

Consider a global economy for which output Y_t at discrete time t is given by

$$Y_t = A_t F_t(\mathbb{K}_t) D_t(S_t), \tag{1}$$

where $A_t F_t(\mathbb{K}_t)$ denotes output absent climate damages, $\mathbb{K}_t$ is a vector of production inputs, and $D_t(S_t)$ captures damages from the atmospheric stock of past carbon dioxide emissions S_t. The stock of carbon emissions is determined by the full history of emissions, that is, $S_t = L(E^t)$, where $E^t \equiv \{E_0, E_1, ..E_t\}$. The flow of emissions E_t is a byproduct of production and satisfies

$$E_t = \phi_t F_t(\mathbb{K}_t), \tag{2}$$

where ϕ_t captures the emissions intensity of production and may vary over time due to changes in technology, sectoral composition, or input use. Aggregate output as measured in the national accounts equals consumption C_t by either consumers or the government plus investment, so that

$$Y_t = C_t + \mathrm{p}_t \mathbb{I}_t, \tag{3}$$

where $\mathbb{I}_t$ is a vector of investments in productive inputs and p_t their relative prices.[13]

We assume that investment goods are competitively priced, so that the price of each investment good reflects the marginal rate of transformation into consumption goods. As we explain later, this implies that standard measures of productivity growth are welfare-relevant in the absence of climate damages. We impose no functional form on the damage function $D_t(\cdot)$ and on the function $L(\cdot)$ that governs how carbon accumulates and depreciates in the atmosphere, or on the drivers of the mapping between the use of production factors and emissions ϕ_t. Hence we nest macro-climate models with explicit assumptions on any or all of these equations (e.g. such as Nordhaus 1992).

[13] Inputs that do not accumulate through investments, such as labor, have zero investment in $\mathbb{I}_t$. Emissions are not recorded as part of the national accounts, even in countries with emissions trading schemes such as the EU ETS. This is because such permits are intermediate inputs or taxes, and thus not part of total value added.

Finally, preferences are such that welfare equals the present value of consumption, along

$$\boldsymbol{V}_t = \mathbb{E}_t \left[\sum_{s=0}^{\infty} \prod_{k=t}^{t+s} \beta_k C_{t+s} \right], \tag{4}$$

where $\mathbb{E}_t$ is the expectation operator and where β_t is the (possibly stochastic) discount factor. Note that the fact that consumption enters linearly in this present value is without loss of generality, given the possibly time-varying discount factor. In subsection 2.4 we show that the expressions for productivity in the next subsection extend directly to settings with concave utility, or where emissions have welfare costs beyond their negative effect on consumption.

2.2. Emissions-adjusted productivity

We define the welfare-relevant measure of productivity in our economy with emissions, TFPE, as the marginal effect of a bundle of inputs $F(\mathbb{K}_t)$ on the welfare V_t:

$$TFPE_t \equiv \frac{\mathrm{d}\, \boldsymbol{V}_t}{\mathrm{d}\, F_t(\mathbb{K}_t)}. \tag{5}$$

Proposition 1 below uses the framework in Section 2.1 to present an intuitive and straightforward to implement expression for TFPE and documents how it differs from standard productivity measures (TFP) that quantify the rate at which inputs convert to outputs:

$$TFP_t \equiv \frac{\partial Y_t}{\partial F_t(\mathbb{K}_t)} = \frac{Y_t}{F_t(\mathbb{K}_t)} = A_t D_t(S_t). \tag{6}$$

Proposition 1. *The marginal effect of inputs on the present value of consumption is given by*

$$TFPE_t = TFP_t \left(1 - \frac{E_t}{Y_t} SCC_t\right), \tag{7}$$

where SCC_t is the social cost of carbon, defined as the present value of the marginal reduction in future consumption caused by an additional unit of emissions:

$$SCC_t \equiv -\mathbb{E}_t \left[\sum_{s=1}^{\infty} \prod_{k=t}^{t+s} \beta_k \frac{dC_{t+s}}{dE_t} \right].$$

Derivation Starting from the definition of TFPE (5) we use the definition of output (3) to write

$$TFPE_t = \frac{\partial V_t}{\partial C_t} \frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial V_t}{\partial \mathrm{p}_t \mathbb{I}_t} \frac{\partial \mathrm{p}_t \mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial V_t}{\partial E_t} \frac{\partial E_t}{\partial F_t(\mathbb{K}_t)}. \tag{8}$$

The first term captures the effect of inputs on today's consumption, the second their effect on investment and thus future consumption, and the third the effect operating through emissions. Under the

competitive pricing of investment goods, the envelope theorem implies that the marginal effects of consumption and investment on welfare are equal. Hence we can write

$$\frac{\partial V_t}{\partial C_t} = \frac{\partial V_t}{\partial \mathrm{p}_t \mathbb{I}_t} = 1 \quad \Rightarrow \quad TFPE_t = TFP_t + \frac{\partial V_t}{\partial E_t} \frac{\partial E_t}{\partial F_t(\mathbb{K}_t)}.$$

which uses that $\partial C_t / \partial F_t(\mathbb{K}_t)$ and $\partial \mathrm{p}_t \mathbb{I}_t / \partial F_t(\mathbb{K}_t)$, sum to $\partial Y_t / \partial F_t(\mathbb{K}_t) = Y_t / F_t(\mathbb{K}_t) \equiv TFP_t$.

The final term in (8) is the product of the marginal welfare cost of emissions and the marginal effect of inputs on emissions. The former is the negative of the Social Cost of Carbon (SCC_t)–a frequently estimated empirical object as discussed in Section 1. The latter is equal to ϕ_t in emissions equation (2). Inverting the emissions function and inserting the production function yields that $\phi_t = TFP_t(E_t/Y_t)$. Inserting ϕ_t and the social cost of carbon into (8) gives

$$TFPE_t = TFP_t - TFP_t \left(\frac{E}{Y_t}\right) SCC_t,$$

and grouping terms yields Proposition 1.

Corollary 1. *In the absence of emissions or if emissions do not harm welfare, i.e.* $SCC_t = 0$, TFP_t *measures the marginal effect of a bundle of inputs* $F_t(\mathbb{K}_t)$ *on the present value of consumption* $\boldsymbol{V}_t$.

Intuition Proposition 1 provides two main insights. First, it shows that adjusting productivity for emissions only requires data on emissions, aggregate output, and the social cost of carbon. The latter serves as a sufficient statistic, that embodies any assumptions on the damage that emissions do to the present value of consumption, be it by lowering the value of the damage function in the production function (1), or by reducing future accumulation of inputs such as capital.

Second, it shows that in the absence of emissions, standard TFP is welfare-relevant in the sense that it equals the marginal effect of inputs on the present value of consumption (Corollary 1). That result is driven by the fact that output is used to produce consumption and investment goods, which means that today's output affects both contemporaneous and future consumption. When investment goods are appropriately priced, the envelope theorem yields that their marginal effect on welfare is equal to the marginal effect of consumption on welfare. Intuitively, that is because the price of investment goods encodes the present value of consumption that will be derived from those goods.[14]

2.3. Productivity at the country level

We have thus far derived TFPE for a closed economy. In practice, domestic damages due to climate change are driven by global emissions. Foreign emissions therefore affect domestic consumption, and domestic emissions affect foreign consumption. For TFP such externalities are not at play, as the effect on consumption and investments are largely confined within the borders.

To adjust productivity for emissions, however, one has to decide whether domestic consumers internalize or ignore the effect that they have overseas. If a country internalizes the effect of its emis-

[14] This intuition extends beyond the first order that we will rely on: Weitzman (1976) derives that when output is measured net of depreciation, it yields the present value of future consumption that will be derived from it.

sions on consumption across countries, the expression for TFPE is largely unchanged. The production function of country i reads

$$Y_{it} = A_{it} F_{it}(\mathbb{K}_{it}) D_{it}(S_t). \tag{9}$$

The welfare-relevant productivity index measures the marginal effect of $F_{it}(\mathbb{K}_{it})$ on the present value of the change in *global* consumption C_t, taking into account that production directly affects domestic consumption and investment investment, and global consumption through a rise in the stock of carbon in the atmosphere:

$$\begin{aligned} TFPE_{it} &= A_{it} D_{it}(S_t) + \mathbb{E}_t \sum_{s=1}^{\infty} \left(\prod_{k=t}^{t+s} \beta_k \frac{\mathrm{d}\, C_{t+s}}{\mathrm{d}\, E_{it}} \frac{\partial E_{it}}{\partial F_{it}(\mathbb{K}_{it})} \right), \\ &= TFP_{it} \left(1 - \frac{E_{it}}{Y_{it}} SCC_t \right). \end{aligned}$$

The fact that domestic consumption is also affected by foreign emissions does not enter the productivity calculation, as domestic production does not directly raise emissions abroad. The marginal damage of domestic emissions on consumption may depend on both the global stock of emissions and the expected path of emissions in other countries—for example, if climate damages are convex in S_t—but this dependence is already captured by the level of SCC_t.

It is equally possible, however, to calculate emissions-adjusted productivity under the assumption that households only internalize domestic climate damages, so that welfare is defined by:

$$\boldsymbol{V}_{it} = \mathbb{E}_t \left[\sum_{s=0}^{\infty} \prod_{k=t}^{t+s} \beta_{ik} C_{it+s} \right], \tag{10}$$

This was the approach used to evaluate climate policy in the United States between 2017 and 2021 (Voosen 2021). To calculate TFPE in this setting, we use estimates of the cost of carbon that focus solely on domestic economic costs, sometimes referred to as the domestic cost of carbon (DCC_t):

$$\begin{aligned} TFPE_{it} \equiv \frac{\mathrm{d}\, \boldsymbol{V}_{it}}{\mathrm{d}\, F_{it}(\mathbb{K}_{it})} &= A_{it} D_{it}(S_t) + \mathbb{E}_t \sum_{s=1}^{\infty} \left(\prod_{k=t}^{t+s} \beta_{ik} \frac{\mathrm{d}\, C_{it+s}}{\mathrm{d}\, E_{it}} \frac{\partial E_{it}}{\partial F_{it}(\mathbb{K}_{it})} \right), \\ &= TFP_{it} \left(1 - \frac{E_{it}}{Y_{it}} DCC_{it} \right). \end{aligned}$$

A practical concern with country-level TFPE measurement is that advanced economies have moved some of their emissions to other countries. This may artificially raise TFPE growth. In the quantification we address this by using trade-adjusted emissions (also known as consumption-based emissions) which, in contrast to territorial emissions, attribute carbon emissions to the country where goods are consumed rather than to where they are produced. Appendix B provides a brief formal motivation for using trade-adjusted emissions series when calculating TFPE – although in

practice the series are highly correlated (e.g., the correlation between growth of trade-adjusted and territorial emissions in the United States is 0.93).[15]

2.4. Extensions

We next present three extensions. The first covers non-consumption costs of climate change, such as the utility cost of higher mortality rates. The second derives TFPE for concave utility. The third explains that it is straightforward to extend our framework to other variables that affect future output, such as research and development. Finally, we discuss how TFPE relates to Green national accounts.

2.4.1. Non-consumption costs of climate change

We have thus far derived TFPE without taking account of any other utility costs of climate change. It is straightforward to show that the expression for TFPE in Proposition 1 can be applied to broader costs, as these simply imply a different definition of the social cost of carbon. Say climate damages impose a non-consumption cost $\Omega(S_t)$, so that welfare net of the damages equals

$$\widetilde{V}_t = \mathbb{E}_t \left[\sum_{s=0}^{\infty} \prod_{k=t}^{t+s} \beta_k \left(C_{t+s} - \Omega(S_{t+s}) \right) \right].$$

An example of what might be included in $\Omega(S_t)$ is a change in old-age mortality, which has large utility costs beyond the direct effect of death on consumption (see, e.g., Carleton et al. 2022). Other forms of environmental progress such as reduced pollution and improvements in air quality, in the spirit of Muller et al. (2011), can also be modeled along these lines.

Defining emissions-adjusted productivity as the change in the present value of consumption net of climate costs, the new expression for TFPE is largely unchanged from Proposition 1:

$$\begin{aligned} TFPE_t \equiv \frac{\mathrm{d}\,\widetilde{V}_t}{\mathrm{d}\,F_t(\mathbb{K}_t)} &= \frac{\partial \widetilde{V}_t}{\partial C_t}\frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \widetilde{V}_t}{\partial \mathrm{p}_t \mathbb{I}_t}\frac{\partial \mathrm{p}_t \mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \widetilde{V}_t}{\partial E_t}\frac{\partial E_t}{\partial F_t(\mathbb{K}_t)}, \\ &= TFP_t \left(1 - \frac{E_t}{Y_t} \widetilde{SCC}_t \right). \end{aligned}$$

In words, the broader costs of climate yield an unchanged expression for TFPE but require an alternative definition of the social cost of carbon, which now includes the marginal increase in the present value of non-consumption climate damages due to carbon dioxide emissions.

2.4.2. Utility

Proposition 1 presents the expression for TFPE as the marginal effect of a bundle of inputs on the present value of consumption. It is also feasible, however, to use the expression for TFPE in Proposition 1 when TFPE is defined as the marginal effect of a bundle of inputs on the present value of

[15] An implication of using trade-adjusted emissions is that a country's TFPE will increase if the emissions-intensities of its imports decline, even when domestic technology is unchanged. In practice, this mechanism is responsible for little of the overall variation of TFPE growth, given the high correlation of trends in territorial and trade-adjusted emissions.

utility. Assuming standard time-separable preferences over consumption and exponential discounting at the constant rate β, we define utility and the related measure of TFPE as follows:

$$\boldsymbol{U}_t = \mathbb{E}_t\left[\sum_{s=0}^{\infty}\beta^s u\left(C_{t+s}\right)\right] \quad , \quad TFPE_t \equiv \frac{\mathrm{d}\,\boldsymbol{U}_t}{\mathrm{d}\,F_t(\mathbb{K}_t)}\frac{1}{u'(C_t)}, \tag{11}$$

where $u(\cdot)$ satisfies the usual properties. We divide the productivity index at time t by the marginal utility of consumption, in order to measure productivity in consumption units. This is a common approach to enable utility comparisons in interpretable units (see, for instance, Adhami et al. 2024).

The resulting expression for TFPE that we derive in (7) is largely unaltered. The sole substantive change is that the final term in the equation, which captures the present value of climate damages, now discounts climate damages with a specific stochastic discount factor:

$$\frac{\partial \boldsymbol{V}_t}{\partial E_t}\frac{1}{u'(C_t)} = \mathbb{E}_t\left[\sum_{s=1}^{\infty}\beta^s\frac{u'(C_{t+s})}{u'(C_t)}\frac{\mathrm{d}\,C_{t+s}}{\mathrm{d}\,E_t}\right],$$

where the expression on the right is a special case of the SCC as defined in Proposition 1: the stochastic discount factor is now pinned down by the levels of consumption and the derivative of the utility function. Beyond this, the other terms in (7) are unchanged. The first partial derivative is unchanged because we divide the productivity index by marginal utility. As long as competitive investment prices reflect the (stochastically discounted) present value of their effect on consumption, the second partial derivative is also unchanged. Thus, imposing a utility function when calculating TFPE merely imposes additional structure on the cost of carbon.

2.4.3. Adjusting productivity for other variables

The framework can be readily applied in settings where variables other than carbon dioxide emissions alter future consumption. Non-carbon greenhouse gases are obvious examples, but so are investments that are not correctly priced in national accounts such as education, or research and development. Denoting the set of these "carbon-like" variables by X_t, we find

$$\begin{aligned}\frac{\mathrm{d}\,\boldsymbol{V}_t}{\mathrm{d}\,F_t(\mathbb{K}_t)} &= \frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \mathrm{p}_t\mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \sum_{X^j\in X}\left(\frac{\partial \boldsymbol{V}_t}{\partial X_t^j}\frac{\partial X_t^j}{\partial F_t(\mathbb{K}_t)}\right), \\ &= TFP_t\left(1 - \sum_{X^j\in X} -\frac{\partial X_t^j}{\partial Y_t}\frac{\partial \boldsymbol{V}_t}{\partial X_t^j}\right).\end{aligned} \tag{12}$$

Thus, if the relationship between X_t^j and both aggregate output and the present value of consumption is known, we can adjust productivity in a similar fashion to how we adjust for carbon in Proposition 1. Our application to carbon seems particularly relevant, both because of the recent comovement of TFP and carbon emissions (Figure 1), and because there exists an abundance of estimates of the social cost of carbon – which makes the adjustment for carbon emissions feasible to implement.

A similar logic can be applied to investment goods that are included in aggregate output but that are mispriced, in the sense that their market price does not fully encode the present value of future consumption to be derived from it – such as R&D. In that case, the final derivative $\partial \boldsymbol{V}_t / \partial X_t^j$ of the adjustment term in (12) would equal the wedge between the input's observed and efficient price.

2.4.4. Green national accounts

In this final extension we briefly point out the close relationship between TFPE and the literature on green national accounts. While we derive TFPE from an integrated assessment model, productivity measured along equation (7) is similar to the productivity index that measures the efficiency with which inputs are transformed into "green GDP": national income net of climate damages.

The literature on green national accounts advocates for subtracting climate damages from national income (see, e.g., Weitzman and Löfgren 1997), building on the seminal contribution by Weitzman (1976). Weitzman explains that national output, if measured as consumption plus investment net of depreciation, in fact captures the welfare that households derive from the entire stream of consumption that investments deliver in the future. Formally, he shows that for constant a interest rate, time-invariant technology, and a linear utility aggregator, a constant consumption path at the current level of net national product yields welfare that is identical to that attained in a competitive equilibrium with no externalities.[16] The green accounting literature argues that climate damages are a negative investment, in the sense that they reduce the remaining stock of natural capital at the economy's disposal. Nordhaus (2021) summarizes this idea, proposing to subtract the product of the social cost of carbon and emissions, labeling the remainder "green GDP". In integrated assessment models, there is an additional indirect cost of climate change on top of this direct effect from negative investment: lower natural capital reduces the incentives for other factor accumulation, further depressing output as climate damages rise.

In Appendix A we show that the productivity index for green GDP is identical to the expression for TFPE that we derive in equation (7), as long as the same social cost of carbon is assumed when subtracting the costs of emissions from aggregate output (capturing both the direct and indirect costs of climate damages). It is straightforward to understand why the productivity indexes for green GDP and for TFPE are identical: when subtracting the product of emissions and the correct social cost of carbon, the remainder is (by definition) the economy's output net of the present value of consumption losses due to emissions.

3. Quantification

We next present quantifications of TFPE for two estimates of the social cost of carbon. To calculate emissions-adjusted total factor productivity, we need data on four variables: carbon emissions, real output, (traditionally measured) productivity, and an estimate of the social cost of carbon. We sum-

[16] The original results in Weitzman (1976) are derived under constant interest rates and discounting, and were extended to settings with time-varying interest rates and stochastic discounting in Weitzman (1998).

marize our data sources in Section 3.1. The social cost of carbon has been extensively estimated in the literature; in Section 3.2 we justify the three values that we use.

3.1. Data

Data on traditionally measured productivity growth and gross domestic product comes from the Penn World Table (edition 11; see Feenstra et al. 2015).[17] We also use purchasing-power-parity (PPP) GDP per capita to analyze how TFPE growth evolves along the development path. To measure carbon emissions, we rely on trade-adjusted CO_2 emissions from Our World in Data (Ritchie et al. 2023), which in turn relies on data from the Global Carbon Project (Andrew and Peters 2024). These are available from 1990. Figure A1 in Appendix C plots emissions for selected countries.

3.2. Social cost of carbon

We adopt an agnostic approach to the social cost of carbon: rather than selecting a particular value, we trace out TFPE under a range of costs. We do so because the empirical literature remains far from settled. Estimates vary widely across methodologies, and there is substantial disagreement—both in academia and policy—about key assumptions underlying damage calculations, including discounting and the treatment of global versus domestic damages. Rather than resolving these debates, we quantify welfare-relevant productivity conditional on specific carbon costs and assess how large damages must be for TFPE to diverge meaningfully from TFP growth.

To this end, we compute TFPE for a social cost of carbon of \$50, \$250 and \$900 per metric ton of carbon dioxide in 2017 (2017 dollars). This range covers most empirical estimates of the marginal global damages of emissions, which are typically between \$50 and \$300 per ton. A recent meta-analysis by Moore et al. (2024), summarizing 1,823 estimates across 147 studies, proposes a central estimate of \$252 when accounting for both consumption and broader damages.[18] Global damages are the standard benchmark in climate policy evaluation (Stern et al. 2022, National Academies of Sciences, Engineering, and Medicine 2017). In the U.S., values of up to \$48 per ton were used in climate policy evaluations during the second Obama administration and at the start of the 2017–2021 Biden administration, rising to \$180 (2017 dollars) by 2023. Thus, our TFPE series at \$50 to \$250 cover the range frequently used by academics and policymakers in cost-benefit analyses.

We also report TFPE under a cost of carbon of \$900, to illustrate the trajectory of welfare-relevant productivity at the upper end of damage estimates. This value is close to the setimate in Bilal and Känzig (2026), who estimate the effect of global temperature shocks on global output. They argue that alternative strategies that study the country-level effects of country-level temperature shocks, under-sample the extreme weather events that determine the true extent of climate damages. While

[17] These productivity series do not account for capital utilization. For the United States and a few European countries, we could use utilization-adjusted series (Fernald 2014, Comin et al. 2025), but, given the strong long-term comovement in growth between utilization-adjusted and unadjusted series, we prefer to harmonize data sources across countries.

[18] Section 2.4 shows that, when climate damages affect utility through channels beyond future consumption, TFPE can still be calculated along (7), using a definition of the social cost of carbon that subsumes these broader damages.

their estimate is clearly an outlier in the literature, quantifying TFPE for these estimates illustrates the effect of recent trends in emissions on the path of productivity if damages are indeed large.

In the main text, we do not include specifications for a social cost of carbon below $50. Lower costs arise under the assumption that countries do not internalize their global climate externality, i.e. when the domestic cost of carbon is used for climate policy cost-benefit analysis. As the domestic cost of carbon is roughly proportional to an economy's share in world output, domestic damages for the U.S. and China are roughly four to five times lower than the social cost of carbon. In addition, countries differ in their exposure to climate damages, to the point that economies such as Canada and Scandinavia may slightly benefit from rising temperatures (Nath et al. 2024). While it is perfectly possible to calculate TFPE based on significantly lower costs – e.g., the whole distribution of domestic carbon costs across countries – this turns out to be redundant: the next section shows that, even at $250, the adjustment to productivity growth is economically small.

Finally, we allow the social cost of carbon to grow at 2.1% per year. The costs grow because proportional damages apply to a growing economy, and because the marginal carbon damage itself might be time-varying. We collect the growth rate implied by a sample of key studies on the social cost of carbon including those reported in Nordhaus (2017) and the Resources for the Future database (Prest et al. 2022). We find little variation in the implied growth rates of the social cost of carbon across time (i.e., within a given model, the social cost of carbon grows at a roughly constant exponential rate) but substantial heterogeneity across models. The median growth rate across these models is 2.1% (which we use), and the corresponding mean is 2.6%.[19]

4. Results

This section presents the results. We start by presenting TFPE in growth rates and compare trends in TFPE growth with trends in traditionally measured TFP growth. We then study the levels of TFP and TFPE, as well as the gap between them. Finally, we discuss the trajectory of TFPE (growth) over the development path. Our focus is on the period from 1990 to 2023, as for this period there exists data on TFP and trade-adjusted emissions for a wide range of countries.

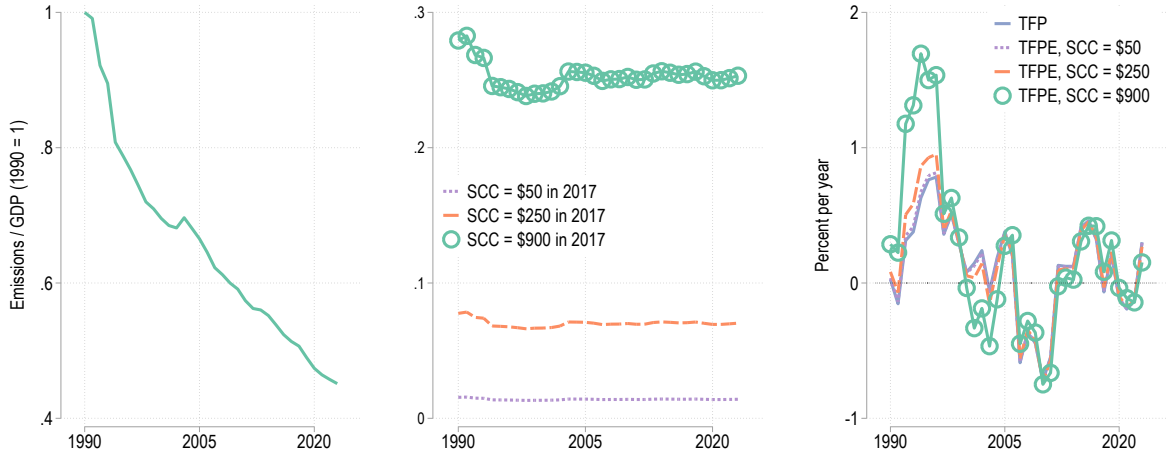
4.1. TFPE growth at the world level

We first present the global path of emissions-adjusted productivity and its drivers in Figure 3. The left-hand figure plots the ratio of global carbon dioxide emissions over world GDP, indexed to unity in 1990.[20] It shows that production has become steadily less emissions intensive since 1990, with the ratio of emissions to GDP falling by around 40%. The center figure multiplies the emissions-to-GDP ratio by the three values of the social costs of carbon, and equals fraction by which traditional productivity (TFP) overstates the efficiency with which inputs are transformed into the present value of consumption. With the exception of the 1990s, and despite the decline in emissions intensity of production, this figure does *not* show a clear downward trend. That is driven by the fact that the

[19] We find close to no correlation between the level of the social cost of carbon and its growth rate across models.

[20] World GDP is defined as the sum of expenditure-side real GDP at chained PPPs, in millions of 2021 US dollars.

Figure 3. Trends in U.S. Total Factor Productivity Growth and Carbon Emissions



(a) Emissions over GDP (b) Emissions over GDP × SCC (c) TFP(E) Growth

Notes: Panel A plots the ratio of global CO_2 emissions to world GDP, indexed to unity in 1990. Panel B plots the environmental damage ratio $dE_t \times \text{SCC}_t / Y_t$, where E_t denotes carbon dioxide emissions (in metric tons), Y_t is world GDP, and SCC_t is the social cost of carbon growing at 2.1% per year. Panel C plots five-year centered moving averages of world TFP growth and world TFPE growth.

social cost of carbon grows at 2.1% per year. Thus, globally, the decline in the emissions intensity of production has been offset by a rise in the marginal damage that emissions do to consumption. By 2023, the figure shows that TFP overstates efficiency by 25% at a social cost of carbon of $900, and 8 and 2% respectively at social costs of carbon of $250 and $50.

The effect of these trends on productivity growth is depicted in the right-hand figure. World TFP growth averaged roughly 0.3% per year over the period. Within-country TFP growth was higher, at around 0.6% per year, but countries with lower TFP levels grew faster. World TFP growth was particularly strong in the 1990s, slowed significantly in the 2000s, as countries with low TFP levels, particularly China, became a large part of the world economy, and then turned negative around the global financial crisis. The key takeaway from the figure is that accounting for the dynamics of emissions raises measured TFP growth in the 1990s, lowers it in the 2000s, and has only a modest positive effect in more recent years.

The adjustment to TFP growth is substantial under a social cost of carbon of $900: under this marginal damage from emissions, the reduction in the emissions intensity of global production in the 1990s causes the growth rate of productivity to more than double. When the SCC is assumed to be $250, the adjustment is small relative to the normal volatility of the TFP series, and TFP and TFPE evolve in a very similar manner. Even for the higher costs of carbon, he qualitative pattern of a growth slowdown beginning in the mid-2000s is unchanged at the global level, even when accounting for climate damages valued at $900 per ton of carbon dioxide.

4.2. TFPE growth at the country level

Given the modest data requirements, TFPE growth can be calculated for most countries across the world. In the coming section, we discuss the recent history of TFPE growth for the United States and a number of other economies in Europe and Asia.[21]

United States Figure 2 presents the TFP and TFPE growth series for the United States. Traditionally-measured TFP growth (the blue solid line) is high in the 1990s through 2005, a boom that is widely ascribed in the literature to the rise of information and communication technology. It then slows down sharply in the early 2000s, and remains persistently low until the recent past; a pattern that is well-documented (e.g. Adler et al. 2017; Goldin et al. 2024).

Turning to emissions-adjusted productivity, we find that the quantitative impact of accounting for emissions at the social cost of carbon of up to $250 per metric ton is small (the purple dotted and orange dashed lines). The TFP-TFPE growth differences rarely exceed 0.1 percentage points per year, and the broad patterns described above remain unaltered. The takeaway from the small adjustment is that, for the social cost of carbon that reflects the recent consensus, global economic costs of emissions are overwhelmed by even minor improvements in productivity.[22]

The path of TFPE changes significantly for a social cost of carbon of $900 (the green circled line). TFPE growth during the 1990s and early 2000s is notably low, remaining well below the TFP growth observed in the earlier part of our sample. The crossover point occurs around 2005, coinciding with the widely discussed timing of the United States' productivity slowdown. Rather than declining over time, TFPE growth increases smoothly from the early 1990s to 2010. The familiar large and persistent slowdown in productivity visible in traditional TFP is no longer visible. Thus, the recent reduction in the emissions-intensity of U.S. production can qualitatively change the path of productivity growth, but only for very high values of the social cost of carbon (i.e., costs that take global damages into account and that are at the very top of existing empirical work, such as the cost estimated by Bilal and Känzig 2026). Conversely, under values for the social cost of carbon more in line with the previous scientific consensus (or those that account for domestic damages only, even using a high domestic cost of carbon) do not lead significant alter to productivity dynamics in the United States.

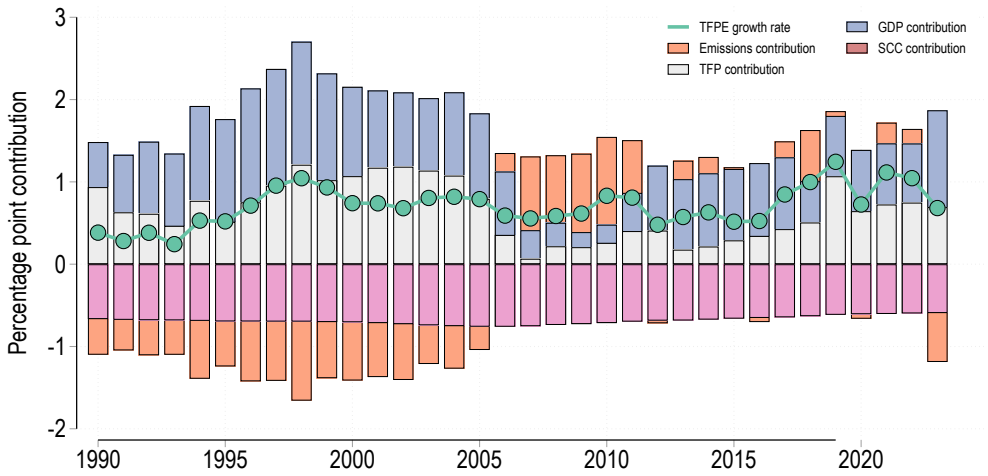
The stable growth of emissions-adjusted productivity under the high social cost of carbon is driven by changes in the emissions intensity of production over time. To show this, Figure 4 decomposes total growth into the contribution of traditional productivity growth, growth in emissions and output, and growth in the social cost of carbon, along

$$\frac{\Delta TFPE_t}{TFPE_{t-1}} = \frac{1}{TFPE_{t-1}}\left[\left(1-\frac{E_{t-1}SCC_{t-1}}{Y_{t-1}}\right)\Delta TFP_t + \left(\frac{E_{t-1}SCC_{t-1}TFP_{t-1}}{Y_{t-1}^2}\right)\Delta Y_t - \left(\frac{TFP_{t-1}SCC_{t-1}}{Y_{t-1}}\right)\Delta E_t - \left(\frac{E_{t-1}TFP_{t-1}}{Y_{t-1}}\right)\Delta SCC_t\right].$$

[21] Appendix C details average TFPE growth for 180 economies worldwide, the full data on which can be accessed via this link.

[22] Note that this also implies the result we previewed earlier: if one uses the domestic cost of carbon instead of the social cost, then growth rates of TFP and TFPE would be virtually indistinguishable.

Figure 4. Drivers of TFPE Growth for the United States (SCC = \$900)



Notes: The figure presents a stacked bar chart that decomposes TFPE growth into the contribution of GDP growth, emissions growth, growth of the social cost of carbon, and growth of TFP. Each series is smoothed using a 5-period centered moving average to mitigate cyclical variation. Each bar gives the partial derivative of TFPE with the respective variable, multiplied by the change in that variable, so that the sum of the bars equals overall TFPE growth (green-circled line).

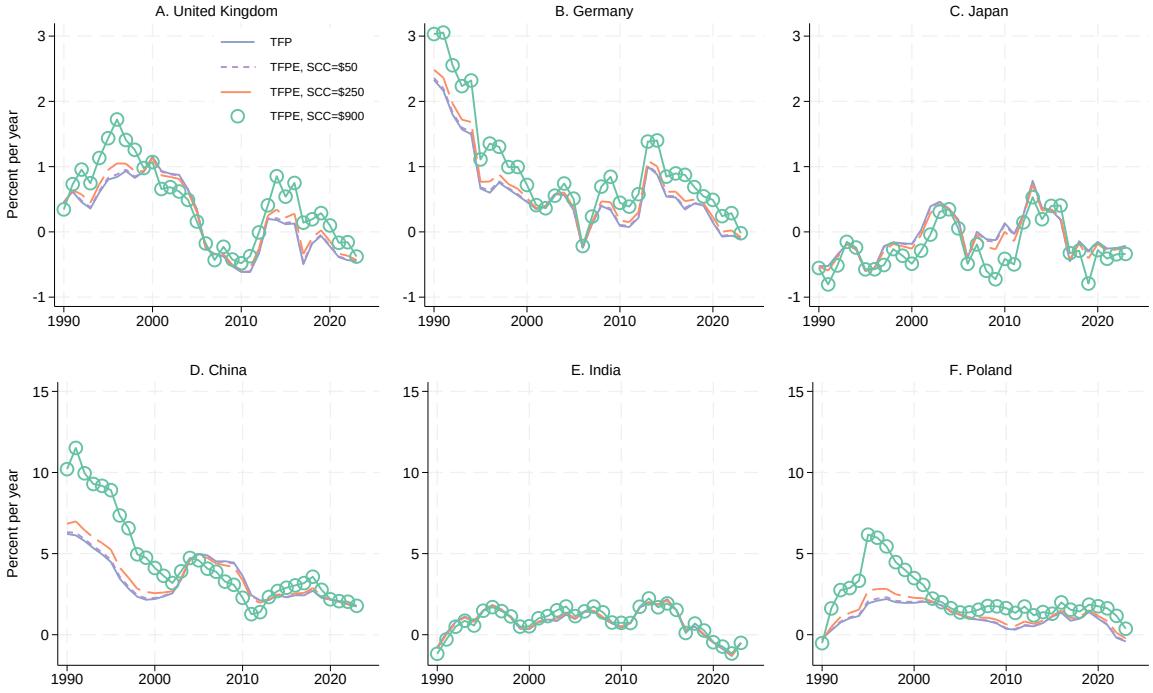
The terms in this decomposition are discrete-time approximations of the partial derivative of TFPE with the respective variable, multiplied by the change in that variable.

The figure shows that the stable TFPE growth is driven by the fact that emissions-intensity of production was rising in the 1990s and the early 2000s, but was falling after 2005. With regard to individual contributors, we note that the main difference between both episodes is carbon emissions, which rose until 2005 and fell in the years that followed. The social cost of carbon has a fairly stable negative effect on the growth of TFPE, which is largely driven by the assumption that costs grow at a 2.1% rate per year (as explained in Section 3.2). GDP growth contributes positively to TFPE growth in all years of the plot, although the contribution is minimal during the Global Financial Crisis, and generally lower in the 2010s than in earlier years.

Cross-country results Figure 5 extends the analysis to six economies spanning a wide range of income levels and emissions trajectories. Several patterns emerge. First, in advanced economies such as the UK and Germany, productivity performance since the global financial crisis improves markedly once emissions are taken into account and damages are valued at \$900 per ton. For example, UK TFP growth in the post-GFC decade up to the Brexit referendum in 2016 is comparable to pre-GFC growth rates. This finding is notable given the extensive literature on the UK productivity puzzle. A similar picture holds for Germany, which effectively experiences a doubling of measured TFP growth once the global impact of greening its economy is taken into account. Meanwhile, the adjustment at \$250 is much less stark.

Adjusting for emissions has an even larger effect on productivity dynamics in emerging and transition economies, represented here by China and Poland. Both countries reduced emissions intensity very substantially during the 1990s. When damages are valued at the high benchmark of \$900

Figure 5. TFP and TFPE growth in selected economies



Notes: Each panel plots average annual growth of TFP (blue lines) and TFPE at a social cost of carbon of $50 per metric ton of carbon dioxide (purple-dotted lines), $250 (orange-dashed lines), and of TFPE at a social cost of carbon of$900 (green-circled lines).

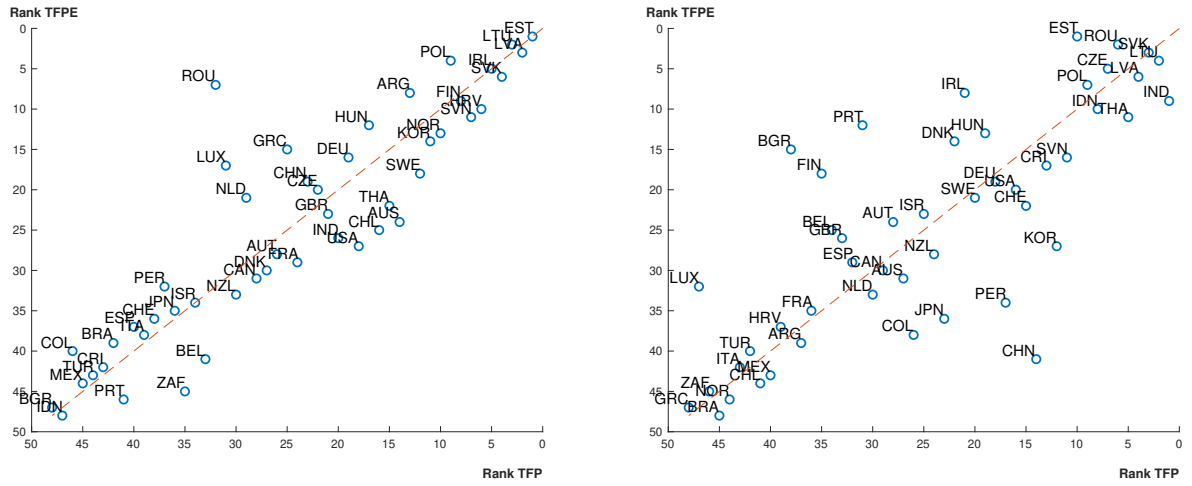
per ton (in 2017 dollars), the emissions adjustment *triples* sustained productivity growth in these economies in the 1990s.

Japan presents a contrasting case. With near-zero conventional TFP growth and a rising damage ratio—reflecting sluggish output growth and a slow decline in emissions—TFPE growth at SCC = $900 turns negative, averaging -0.23% per year. Japan therefore illustrates an economy in which environmental adjustment reveals that measured stagnation understates the true deterioration in productivity once climate damages are taken into account. India occupies an intermediate position: TFP growth averages 1.1% per year, while the environmental adjustment is relatively small, even at high values of the cost of carbon, reflecting an emissions trajectory that has broadly kept pace with output growth.

It is important to highlight that for all economies considered except China, the domestic economy represents only a small share of global activity, implying that purely domestic damages are much smaller than the global SCC. From this perspective, a value of $250 per ton is likely too high if only domestic damages are considered. Even under this assumption, however, productivity dynamics—particularly in recent years—do not differ substantially from those reported in official statistics.

The patterns documented above extend more widely. Across advanced economies, adjusting productivity growth for emissions generally attenuates the post-2005 slowdown, and under high estimates of the social cost of carbon, in some cases reverses it. Figure A2 in the Online Supplemental Material illustrates this broader pattern. The figure compares changes in TFPE growth before and

Figure 6. Comparison of Country Rank for TFP and TFPE Growth



(a) Average for 1990-2005

(b) Average for 2005-2023

Notes: The figures plot the rank of countries in terms of TFP growth (horizontal axis) against their rank in terms of TFPE growth (vertical axis). The figures assume SCC=\$900 in 2017. Growth is given by the percentage change in TFPE along equation (7). Traditionally measured TFP growth is obtained from the Penn World Table. The dashed-red reference line is 45 degrees.

after 2005 with the corresponding changes in traditionally measured TFP growth. In most advanced economies, TFPE growth declines by less than TFP growth, reflecting the widespread fall in emissions intensity over this period. While the magnitude of the adjustment varies across countries, the qualitative pattern of a milder slowdown in emissions-adjusted productivity is common.

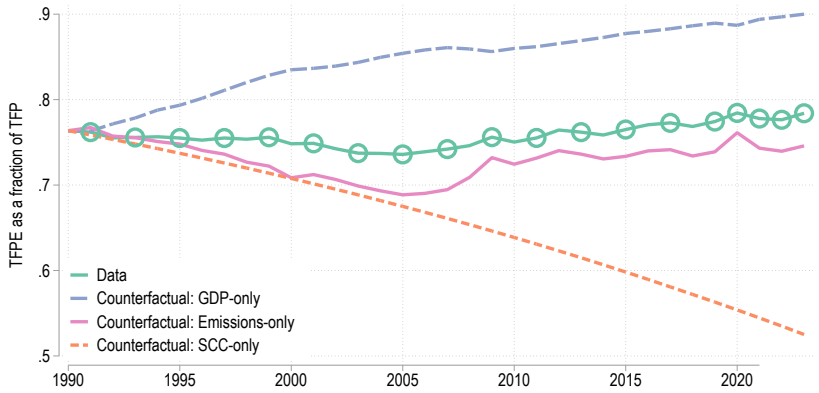
The advanced economies in Figure 5 experience a milder slowdown when productivity growth is adjusted for emissions. For a high social cost of carbon estimate, the slowdown in the United States is even reversed. In Figure A2 of Appendix C we show that this is a general pattern, which reflects the fact that the emissions intensity of production is falling in the majority of advanced countries. The figure compares the change in TFPE growth in the period after 2005 and the period prior to 2005 to the change in TFP growth in the same period. The appendix figure reveals that there are several countries for which TFPE growth has accelerated even as traditionally measured productivity growth slowed down – the pattern we previously documented for the US.[23]

Finally, we show that the divergence of trends in TFPE growth and TFP growth is relatively recent. To do so, we expand the analysis to many countries. Figure 6 presents a scatter plot that ranks countries in terms of average TFP growth against ranks of countries when TFPE growth is used. The left-hand figure is for the earlier years in the data, while the right-hand figure covers the years post-2005. The average growth rates of TFPE across these countries is listed in Table A1 of Appendix C.

The figure shows that countries with high TFP growth typically also had high TFPE growth between 1990 and 2005. There are some geographical patterns in the countries for which TFPE growth

[23]These are the countries in the top-left quadrant of the figure, including Belgium, Denmark, Israel, New Zealand, Canada, and Italy. While this reversal pattern is not universal, the figure also documents that for the majority of the developed economies, TFPE growth has slowed much less than TFP growth. Of the countries shown, the slowdown of TFPE exceeded that of TFP only in South Korea, Greece and Norway.

Figure 7. TFP and TFPE in Levels for the United States



Notes: The green-circled line plots the ratio of TFPE and TFP, that is $\frac{TFPE_t}{TFP_t} = 1 - \frac{E_t}{Y_t} SCC_t$ (see equation (7)), for the high SCC. The other lines plot counterfactual paths for this ratio if only one of the components was changing with the other two held fixed at 1990 levels. For example, the violet-solid line plots the TFPE/TFP ratio if only emissions changed over time, with GDP and SCC fixed at the respective 1990 levels. The figure thus gives the sense of how strong were the underlying drivers of the wedge between TFPE and TFP across countries. Note that the counterfactuals do not add up to the total, since they enter (and thus interact) non-linearly in driving the wedge. Data come from the latest release of the Penn World Table.

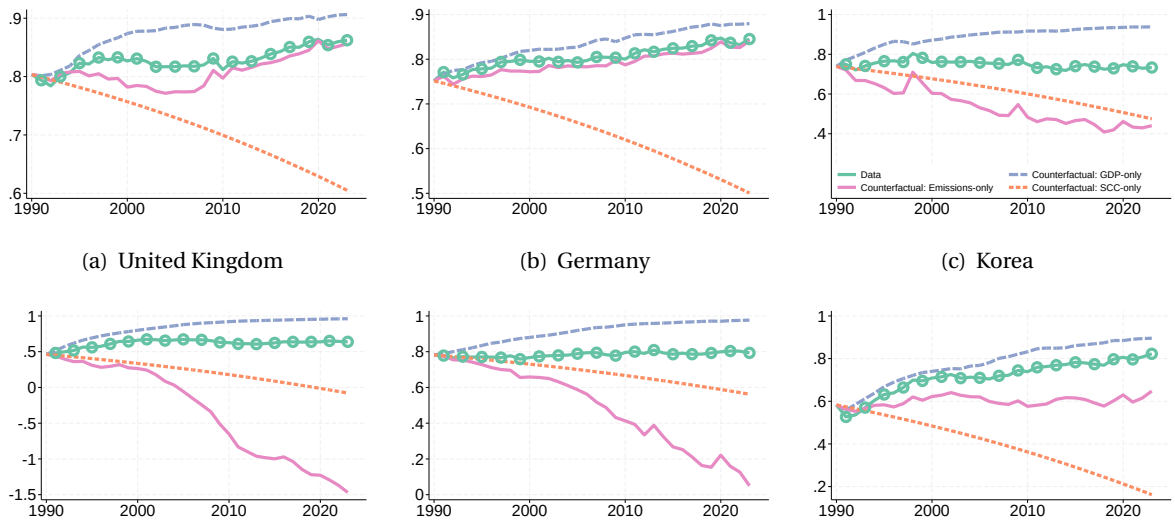
exceeds or falls short of TFP growth. Former member states of the Soviet Bloc such as Romania, Poland and Hungary are all among the countries with a high TFPE rank, reflecting that their emissions did not rise as much as did emissions in other countries with similar rates of productivity growth. Most prominently, however, TFP and TFPE growth are highly correlated in these years.

That is no longer the case in the right-hand figure: TFPE growth appears decoupled from TFP, evidenced by the fact that countries are further away from the 45-degree line (the point at which TFP rank equals TFPE rank). Countries such as Korea, China, Japan, or Peru performing relatively poorly in terms of TFPE growth, while service-sector economies such as Portugal, Ireland, or Finland do better. The greatest degree of re-alignment of country rank occurs among the countries in the middle of the pack, between positions 10 and 30. Overall, it is clear that taking account of growth in emissions intensity can significantly change a country's recent productivity growth standing.

4.3. Levels Gap between TFP and TFPE

In the next set of results we show that TFPE growth alone is not a sufficient yardstick for a country's emissions-adjusted economic performance. Focusing solely on growth can obscure the fact that some countries may already have low emissions intensity from the outset (and therefore higher TFPE relative to TFP, but less space for further TFPE growth in excess of TFP growth). This section therefore analyzes the evolution of the TFP-to-TFPE ratio over time. The TFPE over TFP ratio equals one for an economy without emissions and zero for an economy where emissions cause damages equal to

Figure 8. Ratio of TFPE over TFP: Data and Counterfactuals in Selected Economies



(a) United Kingdom (b) Germany (c) Korea

(d) China (e) Indonesia (f) Poland

Notes: The green-circled line in each subfigure plots the ratio of TFPE and TFP, that is $\frac{TFPE_t}{TFP_t} = 1 - \frac{E_t}{Y_t} SCC_t$ (see equation (7)), for the high SCC. The other lines plot counterfactual paths for this ratio if only one of the components was changing with the other two held fixed at 1990 levels. For example, the violet-solid line plots the TFPE/TFP ratio if only emissions changed over time, with GDP and SCC fixed at the respective 1990 levels. The figure thus gives the sense of how strong were the underlying drivers of the wedge between TFPE and TFP across countries. Note that the counterfactuals do not add up to the total, since they enter (and thus interact) non-linearly in driving the wedge. Data come from the latest release of the Penn World Table.

today's GDP.[24] The ratio has a natural interpretation: it equals the productivity-equivalent gains of achieving net-zero carbon emissions.[25]

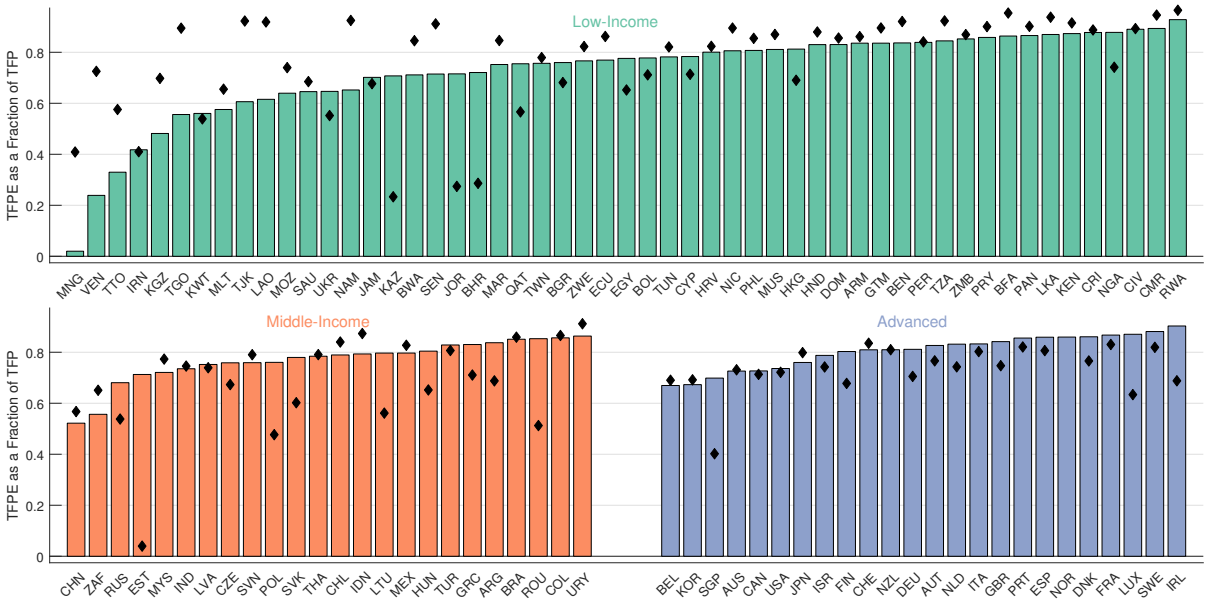
We find stark differences in both the initial level and subsequent growth of the ratio of TFPE over TFP across countries. Figures 7 and 8 plot that ratio for the United States and the selected economies, respectively. Green-circled lines in the figures plot the actual ratio in the data, assuming the high SCC. To identify drivers of the ratio, the other lines provide counterfactual paths for the TFPE over TFP ratios under the assumption that only one of the variables that drives TFPE growth has changed. Violet-solid lines give the path of TFPE over TFP if emissions evolve in the way that they empirically have, holding the SCC and national output at 1990 levels. Blue-long dashed and orange-short dashed lines perform a similar exercise plotting the path of TFPE over TFP if, respectively, only national output or the cost of carbon had evolved, holding other variables constant.

For the United States, the TFPE over TFP ratio varies between 0.7 and 0.75, which means that the U.S. economy was 25% to 30% less productive once the present value of climate damages is taken into account. The ratio equals 0.73 in the final year of the data (2019), which means that achieving zero emissions would yield a productivity increase equivalent to a 27% increase in traditional TFP. The 2019 ratio is higher for the United Kingdom, Germany and Korea, but substantially lower for China

[24] The ratio can even be negative, which occurs when the value of global damages from emissions in a particular country is greater than the value of the outputs that a country produces.

[25] We should note that this quantifies only the productivity gains of achieving net-zero carbon emissions, and not the potential costs of doing so.

Figure 9. The level gap between TFP and TFPE



Notes: The figure plots the $TFPE/TFP$ ratio. The bars are the latest data (2019). The diamonds are data for 1990 (except Namibia, for which it is 1991). The TFP series come from the latest edition of Penn World Table or from the OECD.

and Poland. Between 1990 and 2019, the gap remains reasonably constant in the United States. That is because, despite the fact that both productivity statistics exhibit significantly different growth rates in certain years, their average growth in the U.S. is similar over the full sample.

In line with the decomposition in Figure 4, the effect of the rise in GDP and the rise in the social cost of carbon are of a similar magnitude for the United States, with the latter being slightly larger. This is driven by the fact that we assume a 2.1 growth rate of the SCC over time (as explained in Section 3.1), which is close to the growth rate of U.S. GDP. The slight increase in the TFPE over TFP ratio after 2005 is thus driven by the fall in emissions. A similar pattern is visible in the developed European economies such as the U.K. and Germany, where the TFPE-TFP gap has historically followed the path of emissions closely. In contrast, Asian economies that have seen a decline in their TFPE-to-TFP ratio, such as China and Korea, have predominantly experienced this due to their rapid increase in emissions. China, notably, has seen such a significant rise in emissions that by the mid-2000s, the harm from its emissions growth measured with the 1990 SCC exceeded its 1990 GDP by nearly twofold.

4.4. TFPE along the development path

As a final empirical exercise, we examine how TFPE evolves along the development path. In contrast to the well-known stylized fact that productivity levels are higher in developed economies, we find no clear relationship between TFPE over TFP (or TFPE growth) and the level of development. To show this, we start by analyzing developments in the ratio of TFPE over TFP for all countries in the dataset. Results are provided in Figure 9. Bars in the figure present the ratio of TFPE over TFP in

2019; diamonds give the ratio for 1990. Countries are grouped into low-income, middle-income, and advanced economies.

A number of results stand out. First, the figure again shows that if TFPE is to be a yardstick of a country's emissions-adjusted economic performance, it is important to rely on its level rather than its growth rate. Among the high-income group, for example, countries like Portugal, Spain, France and Sweden had TFPE over TFP ratios of at least 0.8 at both the beginning and the end of the sample. These countries' emissions intensities are low to begin with, so that room to achieve TFPE growth in excess of TFP growth is relatively limited.

Second, the figure shows that there is no clear relationship between income and the ratio of TFPE and TFP. Instead, the figure shows that there is significant heterogeneity in the ratio of TFPE over TFP within income groups. Among lower-income countries, Mongolia's productivity is dwarfed by the carbon intensity of its production, which is driven by the fact that the country relies heavily on coal in energy production (Guo et al. 2020). Lower-income countries in Africa such as Nigeria and Rwanda have relatively low emissions, however, and their ratio of TFPE and TFP is therefore comparable to the ratio in the cleanest high-income countries.

Third, while the level of the TFPE-TFP gap appears uncorrelated with a country's level of development, there is a clear pattern across these three groups in cumulative change: over these 30 years, many of the poor nations recorded significant declines in TFPE-TFP ratio, while most advanced economies recorded improvement.

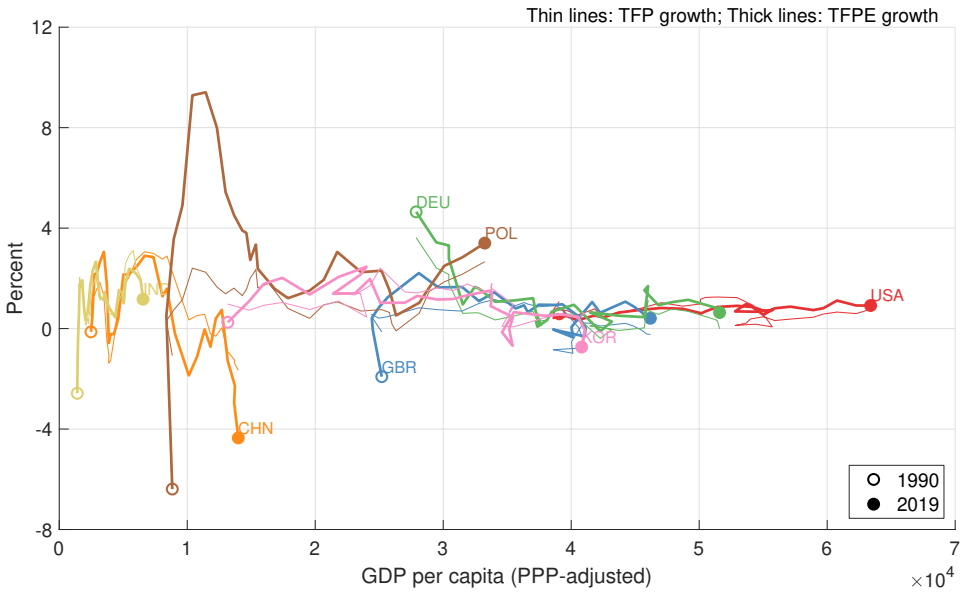
Narrowing in on the third result, we find that the positive relationship between TFPE growth and development status is not one of historical regularity. We show this by plotting the path of a country's TFPE growth against its historical per-capita income (Figure 10). If there is indeed a time-invariant relationship between economic development and TFPE growth, we should see that these are positively related. The figure plots a 5-year moving average of TFPE growth against the 5-year average of per capita income, measured in 2017 dollars adjusted for purchasing power parity. We plot only a few selected economies that reflect the broader patterns we see in the data.

The figure shows both mild patterns of convergence and – predominantly – substantial heterogeneity in how TFPE and TFP diverge at different levels of development. For both TFPE (thick lines) and TFP (thin lines), productivity growth is somewhat higher for developing countries than for advanced economies.[26] In comparison to the emerging markets, advanced economies also record more uniform growth rates of productivity. The gap between TFP and TFPE growth emerged at lower levels of per capita income in European countries, compared to the United States. This is both because emissions started declining earlier in European countries, and because the United States remains richer in terms of per-capita income.

There is substantial heterogeneity nonetheless. The slowdown of TFPE growth occurred at lower levels of income and was much larger in China, for example, which has seen deeply negative TFPE growth at income levels where other countries managed to achieve positive growth. Another country that stands out is Poland, where the transformation from a centrally planned, heavy-industry econ-

[26]The convergence shown here is much less pronounced compared to a plot that charts labor productivity growth, as opposed to TFP growth (not shown here). This is because much of convergence occurs through capital deepening.

Figure 10. TFP and TFPE growth rates along the development path



Notes: The figure plots GDP per capita, measured in PPP 2017 U.S. dollars, against growth rates of TFP (dashed lines) and TFPE (solid lines). Both variables are shown as a 5-year moving average. The countries are: India, China, Poland, United Kingdom, Germany, South Korea, and the United States. The data come from the latest release of the Penn World Table.

omy in the 1990s led to a decent pace of TFP growth but an exceptionally high rate of TFPE growth. This qualitative pattern is common among Central and Eastern European economies, and highlights the markedly different development paths taken by these countries and China.

5. Conclusion

This paper proposes a new productivity metric, TFPE, that adjusts for the climate damage induced by carbon dioxide emissions. TFPE measures the rate at which the economy transforms bundles of inputs into the present value of consumption, taking into account the effect of emissions on future production. Building on the extensive literature that studies interactions between the macroeconomy and climate damages, we show that TFPE is the welfare-relevant measure of productivity in canonical integrated assessment models. TFPE is also the relevant measure of productivity when adjusting economic activity for climate damages in the form of "green national accounts". TFPE is straightforward to calculate under standard (and general) assumptions. It requires an estimate of the social cost of carbon, as well as data on carbon emissions, real GDP, and (traditionally measured) TFP growth.

We find that both trends and relative country performance differ significantly between TFPE and traditional measures of total factor productivity, but only when high estimates for the social cost of carbon are used. For the United States, we find that growth in TFPE has increased slightly since the mid-2000s. This increase is driven by a significant reduction in carbon emissions: trade-adjusted emissions have fallen by 22% since their peak, and the ratio of emissions to GDP has fallen by 40%. The climate damages prevented by the fall in emissions are sufficiently large to offset the slowdown in

traditional measures of productivity. In cross-country comparisons we see that the U.S. experience is not universal. Southeast Asian countries such as China, Korea and Japan have not seen the kind of reduction in emissions observed in the U.S., which lowers their TFPE growth. For China, the increase in emissions is sufficiently large to make average emissions-adjusted productivity growth negative in the 2010s.

Our framework offers several avenues for future research. Our estimates are derived in a framework that focuses narrowly on economic damages from carbon emissions (and can readily be extended to other greenhouse gases). But it is increasingly recognized that climate change has far-reaching consequences beyond its effects on production. The framework can naturally be extended to capture such broader adverse effects, encompassing environmental, biological, and other wide-ranging costs of climate change. It could also be used to adjust productivity growth for mispriced variables unrelated to the climate that, nevertheless, affect consumption in the future.

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‘Emissions-Adjusted Total Factor Productivity’ Appendix

Appendix A. TFPE and green accounting

In this appendix we first review the insight of Weitzman (1976), which states that, under specific conditions —- linear utility in consumption, no technological progress, a constant real interest rate, and a competitive equilibrium with no externalities – net national product represents the annuity value of welfare in competitive equilibrium. We then show how the damage function analysis on which we build connects to this insight, particularly how the intertemporal nature of TFPE recovers the welfare-relevant measure of productivity, at least within this stylized model. The philosophy of this exercise is to focus on an environment where Weitzman’s insight holds exactly and then examine how the TFPE approach links to green, or comprehensive, accounting.

A.1. Review of the Weitzman (1976) insight

Notation is as follows. L is (constant) labor, N is a stock of natural (environmental) capital, E is emissions which is equal to the negative net investment in the stock of natural capital N: $\frac{\partial N(t)}{\partial t} = -E$. We denote with μ the price of a unit of natural capital. Let $\mathscr{S}(L,N)$ be the production possibilities set at time t. Following Weitzman (1976), time is continuous. Net national product (NNP), defined as national product net of the depreciation of production inputs, is given by the function

$$Y(L,N,\mu) := \max_{C,E \in \mathscr{S}(L,N)} C - \mu E,$$

where μ is the price of the (negative) investment in natural capital.

Consider a dynamic, continuous-time competitive equilibrium with no externalities. We denote variables in the competitive equilibrium with an asterisk. In such equilibrium two equations hold:

$$Y^*(t) := Y(L,N^*,p) = C^* - \mu E^* \tag{A.1}$$

$$\frac{\partial Y}{\partial N}\Big|_* = r\mu - \dot{\mu}. \tag{A.2}$$

The first equation says that what is actually produced by the economy at any time maximizes its income: in other words, relative prices are equal to marginal rates of transformation. The second equation is the optimality condition for natural capital, which can be rewritten as $r = \frac{\partial Y/\partial N}{\mu} + \frac{\dot{\mu}}{\mu}$. In words, the required return is equal to the dividend rate plus capital gain.

The primary argument in Weitzman (1976) is that welfare in the competitive equilibrium at time t is the same as welfare that would be generated by a constant consumption path, with consumption equal to the (constant) $NNP(t)$ forever:

$$W^*(t) := \int_t^\infty e^{-r(s-t)} C^*(s) ds = \int_t^\infty e^{-r(s-t)} NNP(t) ds = \frac{Y^*(t)}{r}.$$

Thus, the current value of NNP is the annuity value of competitive equilibrium welfare:

$$Y^*(t) = r \int_t^\infty e^{-r(s-t)} C^*(s) ds = r W^*(t).$$

Proof. To see this, totally differentiate $Y(L, N^*, \mu)$; recalling that L is constant,

$$\frac{dY^*}{dt} = \frac{\partial Y^*}{\partial N^*} \frac{dN^*}{dt} + \frac{\partial Y^*}{\partial \mu} \frac{d\mu}{dt},$$

and note that $\frac{dN^*}{dt} = -E^*$ and $\frac{\partial Y^*}{\partial \mu} = -E^*$by the first competitive equilibrium equation above and the envelope theorem. Thus:

$$\frac{dY^*}{dt} = -(r\mu - \dot{\mu}) E^* + -E\dot{\mu} = -r\mu E^* = r(Y^*(t) - C^*(t)).$$

Solving this differential equation yields

$$Y^*(t) = r \int_t^\infty e^{-r(s-t)} C^*(s) ds.$$

A.2. Relationship between the social cost of carbon and μ

Recall that the competitive equilibrium above is efficient. Thus, we might anticipate that the competitive prices reflect the true social marginal rates of substitution. In the case of emissions of CO2, we might anticipate that μ is equal to the social cost of carbon. We now show more formally that this is indeed the case. Solving (A.2) we obtain

$$\mu(t) = \int_t^\infty e^{-r(s-t)} \frac{\partial Y}{\partial N}(s) ds.$$

Furthermore, we now combine this with the damage function specification for (net) output. Assume

$$Y = ALD(N) = ALD(S) \quad \dot{S} = -\dot{N} = E,$$

where L is (constant) labor, A is a constant productivity term, N is a stock of natural capital, S is the deviation of CO2, from the pre-industrial stock, $D(\cdot)$ is a damage function, with $D' \not\equiv 0$. Then

$$\mu(t) = \int_t^\infty e^{-r(s-t)} ALD'(N(s)) ds = -AL \int_t^\infty e^{-r(s-t)} \frac{\partial D(S(s))}{\partial S(s)} ds =$$

$$= -AL \int_t^{\infty} e^{-r(s-t)} \frac{\partial D(S(s))}{\partial E(t)} \frac{\partial E(t)}{\partial S(s)} ds.$$

In this simple model we have $\frac{\partial E(t)}{\partial S(s)}$ is $1/\frac{\partial S(s)}{\partial E(t)} = 1/1 = 1$. Thus,

$$\mu(t) = -AL \int_t^{\infty} e^{-r(s-t)} \frac{\partial D(S(s))}{\partial E(t)} ds = SCC(t),$$

which follows from our definition of the SCC in the main text. So by Weitzman (1976), we should use $NNP := C^* - SCC \times E^*$as an income measure that is informative of welfare.

A.3. TFP and TFPE

We next show that TFPE is the welfare-relevant measure of productivity when output is measured through green NNP - that is, it is measured as output adjusted for depletion of natural capital.

TFP: If TFP was calculated in terms of the appropriately estimated net national product, then TFP would be the correct measure of productivity:

$$TFP \equiv \frac{\partial Y(t)}{\partial L(t)} = A(t)D(N(t)).$$

However, the way we traditionally measure productivity is with GDP. Consequently, TFP reported by statistical agencies worldwide is, in terms of the variables defined in the model here, given by:

$$\frac{\partial (Y(t) + \mu(t)E(t))}{\partial L(t)} = \frac{\partial Y(t)}{\partial L(t)} + \mu(t)\frac{\partial E(t)}{\partial L(t)} = \frac{\partial Y(t)}{\partial L(t)} + \mu(t)\phi(t),$$

where $\phi(t)$ satisfies $E(t) = \phi(t)L(t)$. This measure overestimates the welfare-relevant TFP by not subtracting the value of emissions that the economy generates.

TFPE: In the context of the model presented in this Appendix, we define TFPE as follows:

$$\begin{aligned}
TFPE(t) \equiv \frac{\partial V(t)}{\partial L(t)} &= \frac{\partial \left(\int_t^{\infty} e^{-r(s-t)} C(s) ds \right)}{\partial L(t)} = \frac{\partial \left(\int_t^{\infty} e^{-r(s-t)} \left(Y(s) + \mu E(s) \right) ds \right)}{\partial L(t)} \\
&= \frac{\partial \left(\int_t^{\infty} e^{-r(s-t)} \left(A(t)L(t)D(N(s)) + \mu(s)E(s) \right) ds \right)}{\partial L(t)} \\
&= A(t)D(N(t)) + A(t)L(t) \int_t^{\infty} e^{-r(s-t)} \left(\frac{\partial D(N(s))}{\partial E(t)} \frac{\partial E(t)}{\partial L(t)} \right) ds + \mu(t)\frac{\partial E(t)}{\partial L(t)} \\
&= A(t)D(N(t)) + A(t)L(t) \int_t^{\infty} e^{-r(s-t)} \left(\frac{\partial D(N(s))}{\partial E(t)} \phi(t) \right) ds + \mu(t)\phi(t) \\
&= A(t)D(N(t)) + \phi(t)A(t)L(t) \int_t^{\infty} e^{-r(s-t)} \left(\frac{\partial D(N(s))}{\partial E(t)} \right) ds + \mu(t)\phi(t) \\
&= A(t)D(N(t)) - \mu(t)\phi(t) + \mu(t)\phi(t) = A(t)D(N(t))
\end{aligned}$$

This shows that TFPE is indeed the welfare-relevant measure of productivity. Our framework is thus consistent with and bridges the two canonical traditions in the climate literature: the green accounting literature and the literature on integrated assessment models and damage functions.

Appendix B. Territorial versus trade-adjusted emissions

We rely on trade-adjusted emissions, also known as consumption-based emissions, to calculate TFPE. These measure the total amount of emissions involved with consumption in a country. This is in contrast to territorial emissions, also known as production-based emissions, which instead measure total emissions involved in domestic production. Both are equal at the global level. At the country level, consumption-based emissions exceed territorial emissions in many advanced economies, including the United States and most of Europe. High-export countries such as China instead feature higher territorial emissions than consumption-based emissions.

The use of consumption-based emissions is motivated by a simple extension of the framework. Rather than using the closed economy's emissions function, assume that emissions E_{it} in any country i are driven by a combination of domestic production and production in every other country in the world. Total emissions are given by

$$E_{it} = \sum_{j \in J} \phi_{ijt} F_{jt}(\mathbb{K}_{jt}),$$

where J denotes the set of countries in the world economy, including i. In this framework, emissions-adjusted productivity is given by

$$TFPE_{it} = \frac{\partial C_{it}}{\partial F_{it}(\mathbb{K}_{it})} + \frac{\partial \mathrm{p}'_{it} \mathbb{I}_{it}}{\partial F_{it}(\mathbb{K}_{it})} + \left(\frac{\partial \boldsymbol{V}_{it}}{\partial E_t} \left[\sum_{j \in J} \frac{\partial E_{jt}}{\partial F_t(\mathbb{K}_t)} \right] \right),$$

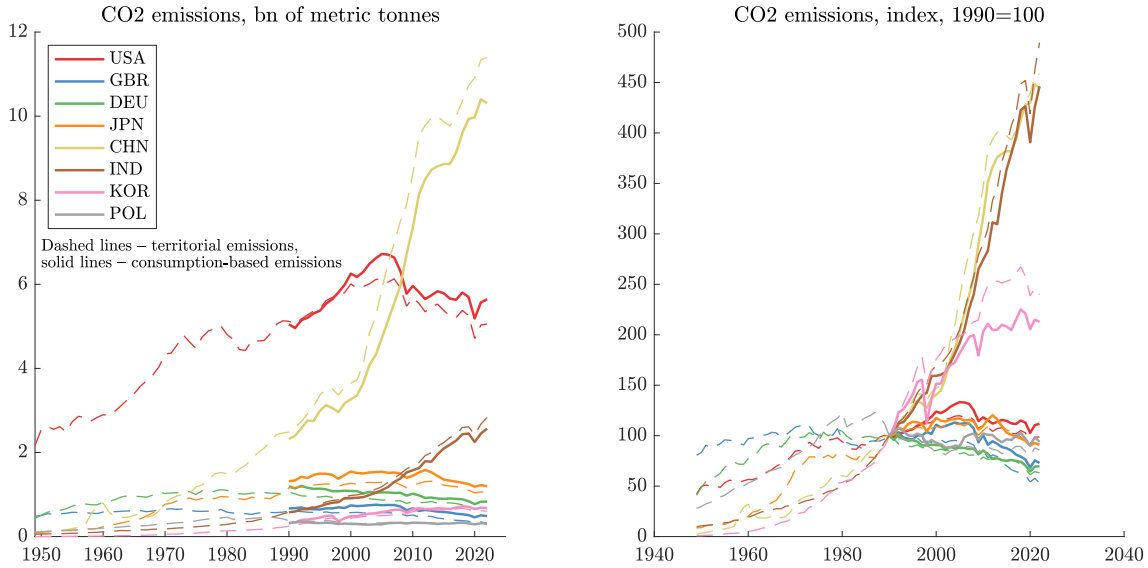
where E_t denotes global emissions, $E_t = \sum_{j \in J} E_{jt}$. Rewriting yields the familiar TFPE expression,

$$\begin{aligned} TFPE_{it} &= TFP_{it} - SCC_{it} \left[\sum_{j \in J} \phi_{jt} \right], \\ &= TFP_{it} - TFP_{it} \frac{\sum_{j \in J} \left(E_{jt} - \sum_{h \neq i} \phi_{jht} F_{ht}(\mathbb{K}_{ht}) \right)}{Y_{it}} SCC_{it}, \\ &= TFP_{it} \left(1 - \frac{\tilde{E}_{it}}{Y_{it}} SCC_{it} \right), \end{aligned}$$

where $\tilde{E}_{it} \equiv \sum_{j \in J} \left(E_{jt} - \sum_{h \neq i} \phi_{jht} F_{ht}(\mathbb{K}_{ht}) \right)$ equals trade-adjusted or consumption-based emissions.

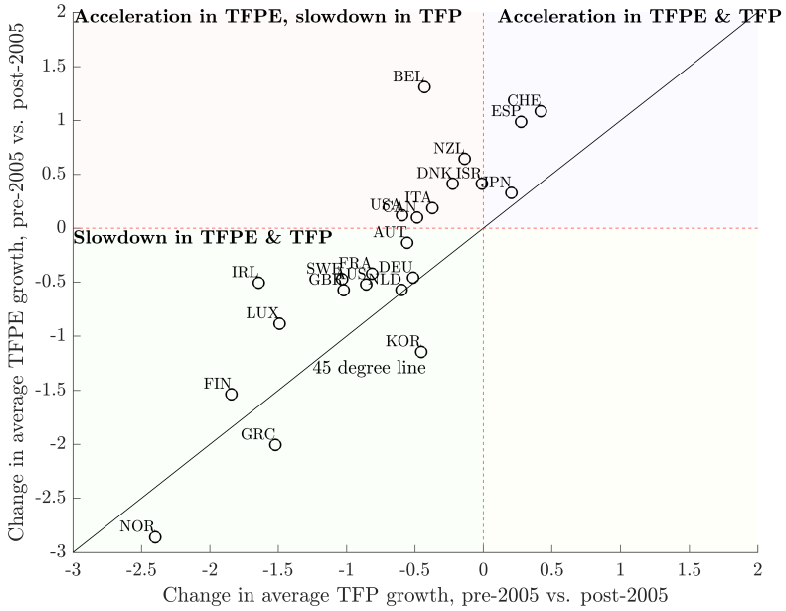
Appendix C. Additional Tables and Figures

Figure A1. Carbon Dioxide Emissions in Selected Economies



Notes: This figure plots the path of annual territorial and trade-adjusted/consumption-based CO_2 emissions from Our World in Data (Ritchie et al. 2023). The left-hand figure plots emissions in billions of metric tons across selected countries. The right-hand figure plots an index of emissions, using 1990 as the base year.

Figure A2. Acceleration and slowdown in long averages of TFP and TFPE growth



Notes: The figure plots the difference between the average growth of TFP between 1990 and 2005 and the average growth rate of TFP between 2006 and 2022 (on the x-axis) against the equivalent difference in terms of TFPE (on the y-axis), under the assumption of a social cost of carbon of $900 per metric ton.

Table A1: Average TFP and TFPE growth 1990-2005 and 2006-2019 - Part 1

	Growth (%) 1990-2005			Growth (%) 2006-2019			Wedge 1990-2005		Wedge 2006-2019	
	TFP	TFPE	TFPE	TFP	TFPE	TFPE	TFPE vs. TFP		TFPE vs. TFP	
SCC		$250	$900		$250	$900	$252	$900	$250	$900
ARG	1.16	1.43	2.44	-0.32	-0.28	-0.14	0.27	1.27	0.04	0.18
ARM	10.70	10.48	9.95	3.75	3.83	4.31	-0.23	-0.75	0.08	0.56
AUS	1.16	1.11	0.93	0.07	0.11	0.27	-0.05	-0.24	0.04	0.20
AUT	0.48	0.50	0.56	0.05	0.15	0.50	0.01	0.07	0.10	0.45
BEL	0.19	0.01	-0.72	-0.23	-0.10	0.47	-0.18	-0.91	0.13	0.70
BEN	0.60	0.42	-0.12	1.69	1.71	1.96	-0.18	-0.72	0.02	0.27
BFA	1.81	1.78	1.69	0.13	-0.00	-0.40	-0.03	-0.12	-0.13	-0.53
BGR	-1.08	-1.21	-1.51	-0.41	-0.13	1.02	-0.13	-0.43	0.28	1.43
BRA	-0.53	-0.53	-0.51	-0.98	-1.00	-1.06	0.01	0.03	-0.02	-0.08
BWA	-2.03	-1.89	-1.43	-1.78	-2.16	-3.30	0.14	0.60	-0.38	-1.51
CAN	0.41	0.37	0.24	-0.02	0.04	0.28	-0.04	-0.17	0.06	0.30
CHE	-0.13	-0.21	-0.44	0.43	0.46	0.60	-0.08	-0.31	0.03	0.17
CHL	1.10	1.04	0.85	-0.65	-0.69	-0.81	-0.06	-0.24	-0.04	-0.15
CHN	0.61	0.71	1.18	0.69	0.51	-0.34	0.10	0.57	-0.18	-1.03
CMR	-0.44	-0.52	-0.73	-0.01	-0.03	-0.10	-0.08	-0.29	-0.03	-0.10
COL	-0.83	-0.81	-0.72	0.10	0.06	-0.07	0.03	0.12	-0.04	-0.17
CRI	-0.54	-0.60	-0.77	0.83	0.87	1.00	-0.06	-0.23	0.04	0.17
CYP	1.61	1.60	1.66	-0.23	-0.08	0.50	-0.01	0.04	0.15	0.73
CZE	0.69	0.76	1.06	1.27	1.42	1.99	0.07	0.36	0.15	0.72
DEU	0.89	1.00	1.42	0.36	0.46	0.81	0.11	0.54	0.10	0.45
DNK	0.47	0.46	0.44	0.25	0.44	1.08	-0.01	-0.02	0.19	0.82
DOM	0.37	0.23	-0.02	0.82	0.94	1.87	-0.14	-0.39	0.12	1.05
ECU	-0.06	-0.25	-0.81	0.09	0.10	0.13	-0.19	-0.74	0.01	0.04
EGY	-1.44	-1.18	-0.17	-0.72	-0.71	-0.67	0.25	1.27	0.01	0.05
ESP	-0.40	-0.42	-0.49	-0.15	-0.03	0.37	-0.02	-0.09	0.12	0.52
EST	4.37	4.71	9.23	0.92	1.64	5.71	0.34	4.87	0.72	4.79
FIN	1.59	1.63	2.07	-0.24	-0.01	0.85	0.03	0.47	0.23	1.09
FRA	0.60	0.58	0.54	-0.25	-0.17	0.10	-0.02	-0.06	0.08	0.35
GBR	0.76	0.80	0.94	-0.19	-0.05	0.44	0.04	0.19	0.15	0.63
GRC	0.60	0.79	1.48	-1.22	-1.17	-0.98	0.19	0.88	0.05	0.24
GTM	0.04	0.07	0.33	-0.06	-0.18	-0.56	0.03	0.29	-0.13	-0.50
HND	-1.19	-1.27	-1.45	-0.36	-0.33	0.73	-0.07	-0.26	0.03	1.10
HRV	2.15	2.12	2.04	-0.48	-0.39	-0.06	-0.03	-0.11	0.09	0.41
HUN	1.09	1.24	1.86	0.35	0.52	1.12	0.14	0.77	0.17	0.77
IDN	-0.90	-1.13	-1.85	1.16	1.22	1.46	-0.23	-0.95	0.07	0.30
IND	0.80	0.80	0.80	1.66	1.64	1.57	-0.00	0.00	-0.02	-0.08
IRL	2.25	2.36	2.79	0.26	0.59	1.66	0.10	0.54	0.32	1.39
ISR	0.02	0.01	0.02	0.11	0.21	0.56	-0.00	0.01	0.09	0.45
ITA	-0.40	-0.42	-0.51	-0.82	-0.74	-0.47	-0.03	-0.11	0.08	0.36
JAM	-0.53	-0.39	0.38	-0.51	-0.59	-0.84	0.15	0.91	-0.08	-0.33
JOR	-0.41	0.05	4.56	-1.13	-0.61	1.98	0.46	4.97	0.52	3.11
JPN	-0.08	-0.13	-0.30	0.18	0.16	0.07	-0.05	-0.22	-0.03	-0.12
KAZ	2.83	3.10	8.36	1.88	2.59	6.76	0.27	5.54	0.72	4.88
KEN	-2.02	-2.06	-2.17	0.39	0.35	0.24	-0.04	-0.15	-0.04	-0.15
KGZ	2.67	2.62	7.25	0.40	0.23	5.06	-0.05	4.58	-0.18	4.65
KOR	1.28	1.35	1.64	0.89	0.79	0.43	0.07	0.36	-0.10	-0.46
KWT	6.50	6.83	8.61	-5.63	-5.86	-6.42	0.33	2.11	-0.23	-0.79

Table A2: Part 2

	Growth (%) 1990-2005			Growth (%) 2006-2019			Wedge 1990-2005		Wedge 2006-2019	
	TFP	TFPE	TFPE	TFP	TFPE	TFPE	TFPE vs. TFP		TFPE vs. TFP	
SCC		$250	$900		$250	$900	$250	$900	$250	$900
LKA	0.66	0.51	0.09	0.60	0.61	0.65	-0.15	-0.57	0.01	0.05
LTU	3.48	4.24	7.99	1.41	1.56	2.14	0.76	4.51	0.16	0.73
LUX	0.36	0.56	1.40	-1.09	-0.81	0.22	0.20	1.04	0.28	1.31
LVA	3.98	4.10	4.67	1.35	1.47	1.91	0.12	0.69	0.11	0.56
MAR	-0.72	-0.86	-1.30	1.01	0.97	0.81	-0.14	-0.58	-0.05	-0.20
MEX	-0.68	-0.77	-1.06	-0.61	-0.59	-0.50	-0.09	-0.38	0.02	0.11
MLT	0.71	0.82	1.32	0.96	0.73	0.15	0.10	0.61	-0.24	-0.81
MOZ	4.10	4.28	4.98	-1.19	-1.52	-2.31	0.17	0.88	-0.33	-1.12
MUS	0.82	0.69	0.27	0.61	0.63	0.68	-0.13	-0.55	0.01	0.06
MYS	-0.63	-0.63	-0.63	0.15	0.05	-0.27	-0.01	-0.00	-0.09	-0.42
NAM	1.61	1.40	0.80	-1.56	-2.00	-3.38	-0.22	-0.81	-0.45	-1.83
NIC	-0.13	-0.29	-0.77	-0.52	-0.54	-0.61	-0.15	-0.63	-0.02	-0.10
NLD	0.40	0.53	1.04	-0.08	-0.03	0.16	0.13	0.64	0.05	0.25
NOR	1.51	1.61	1.75	-0.92	-0.92	-0.89	0.05	0.19	0.01	0.03
NZL	0.38	0.32	0.15	0.15	0.20	0.38	-0.05	-0.23	0.05	0.23
PAN	-0.27	-0.64	-0.67	-1.25	-2.77	-3.81	-0.01	-0.04	-0.38	-1.41
PER	-0.11	-0.05	0.15	0.39	0.33	0.14	0.06	0.26	-0.06	-0.25
PHL	-0.23	-0.30	-0.52	1.28	1.25	1.18	-0.07	-0.29	-0.02	-0.09
POL	1.54	1.97	4.15	0.97	1.15	1.85	0.42	2.61	0.18	0.88
PRT	-0.43	-0.66	-1.46	-0.14	0.15	1.19	-0.23	-1.03	0.29	1.33
PRY	-0.47	-0.49	-0.54	0.62	0.56	0.38	-0.02	-0.07	-0.06	-0.24
ROU	0.31	0.72	2.65	1.30	1.59	2.65	0.41	2.34	0.30	1.36
RWA	3.30	3.30	3.28	1.30	1.24	1.07	-0.01	-0.02	-0.06	-0.23
SAU	-0.81	-1.02	-1.62	-3.98	-3.85	-3.08	-0.21	-0.80	0.13	0.90
SEN	0.30	0.17	-0.23	-0.71	-0.96	-1.79	-0.13	-0.54	-0.25	-1.08
SGP	-0.20	0.34	3.46	-0.80	-0.64	0.87	0.53	3.66	0.16	1.67
SVK	2.56	2.59	2.74	1.41	1.61	2.39	0.03	0.18	0.20	0.98
SVN	1.85	1.87	1.95	0.92	0.94	1.01	0.02	0.10	0.02	0.09
SWE	1.25	1.27	1.32	0.29	0.40	0.73	0.01	0.07	0.10	0.43
TGO	-1.43	-1.43	-1.38	3.27	2.69	1.68	-0.00	0.05	-0.58	-1.59
THA	1.11	1.09	1.04	1.30	1.31	1.34	-0.02	-0.07	0.01	0.04
TJK	4.59	3.95	2.72	7.23	7.15	9.25	-0.64	-1.86	-0.08	2.02
TTO	2.90	2.92	5.62	-2.71	-3.14	-3.73	0.03	2.72	-0.44	-1.02
TUN	0.61	0.72	1.10	-0.15	-0.33	-0.90	0.11	0.50	-0.18	-0.75
TUR	-0.65	-0.72	-0.96	-0.72	-0.60	-0.22	-0.08	-0.31	0.11	0.50
TWN	1.76	1.69	1.46	0.93	0.96	1.07	-0.07	-0.30	0.03	0.14
UKR	3.03	2.99	4.31	1.11	1.38	2.68	-0.04	1.27	0.27	1.57
URY	0.23	0.10	-0.27	1.46	1.49	1.58	-0.13	-0.50	0.03	0.12
USA	0.93	0.87	0.65	0.40	0.48	0.80	-0.06	-0.28	0.08	0.40
ZAF	-0.00	-0.22	-1.12	-1.02	-1.00	-0.85	-0.22	-1.12	0.02	0.16
ZMB	1.65	1.59	1.40	0.86	0.89	1.01	-0.07	-0.26	0.03	0.15
ZWE	-3.04	-3.23	-3.86	3.99	4.10	5.72	-0.19	-0.82	0.11	1.74