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 current and future output. We draw on the climate-macro literature to propose a measure for emissions-adjusted total factor productivity (TFPE) that takes these long-run effects into account. TFPE is a 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. For traditional (small) estimates on the economic effects of climate change, TFPE is approximately equal to TFP. For recent (large) estimates of the social cost of carbon, however, TFPE and TFP growth decouple. In the United States, the rapid decline in emissions over the past 20 years raises annual TFPE growth by 0.4 percentage points. In contrast to traditional productivity measures, growth in TFPE accelerates after the mid-2000s. A back-of-the-envelope calculation furthermore finds that achieving net-zero emissions would raise U.S. TFPE by 27%.

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1. Introduction

Productivity is typically defined as the rate at which an economy transforms inputs, such as capital and labor, into outputs. However, what if today's production has significant implications for future output? Increasingly, it's understood that the rising concentration of carbon dioxide in the atmosphere – a byproduct of production since the Industrial Revolution – negatively impacts both the climate and the economy (e.g. Nordhaus 1977 and 1992, Nordhaus and Boyer 2003, Muller et al. 2011, Hassler and Krusell 2018, Bilal and Känzig 2024, Bilal and Stock 2025). An economy that reduces its carbon emissions while maintaining the same level of output can thus be considered, in a sense, more productive. The difference is that lower emissions prevent climate-related damage and thus preserve or enhance our ability to create output in the future, rather than today. To quantify this, we need a productivity measure that integrates both traditional productivity growth and the benefits of reduced emissions.

This paper proposes a measure of total factor productivity that is adjusted for carbon emissions. Drawing on the long literature that relates climate to macroeconomic activity, emissions-adjusted total factor productivity (TFPE) measures the marginal effect of an increase in the economy's use of inputs on the present value of the full path of output, taking the damage of today's emissions on future production into account. It is the welfare-relevant measure of productivity in canonical models that combine macroeconomic analysis with analysis of climate damages, in particular Dynamic Integrated Climate-Economy (DICE) models and "green national accounts". We derive the expression for TFPE using standard assumptions on production, emissions, and intertemporal discounting.

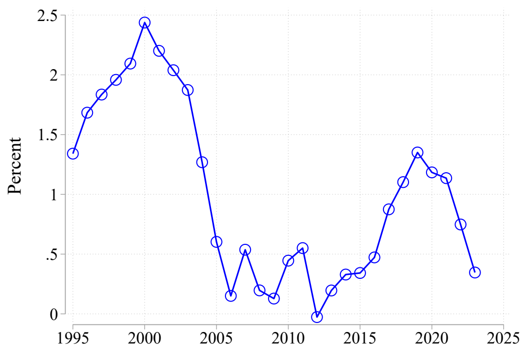
The wedge between TFPE and traditional productivity measures (TFP) is a simple function of the present value of climate damages caused by a marginal increase in emissions – which is the textbook definition of the social cost of carbon (Hassler and Krusell 2018). TFPE thus solely relies on data on TFP, carbon emissions, real GDP, and an estimate of the social cost of carbon. The public availability of such data makes it feasible to calculate TFPE across countries and over long periods of time.

TFPE is forward looking, in the sense that it quantifies the effect of today's production-related emissions on the present value of current and future output. It may seem unconventional to include future output in a measure of productivity, if one thinks of traditional TFP as only capturing the effect of inputs on contemporaneous output. We argue, however, that the forward-looking nature of TFPE is more orthodox than it seems. That is because today's output is used both for consumption and investment. Weitzman (1976) shows that when investment goods are appropriately priced, net investment encodes the present value of future consumption that results from it. Just as TFPE, productivity statistics that measure the rate at which input bundles generate net output are therefore also dynamic, in the sense that they capture the effect of today's inputs on future consumption.[1]

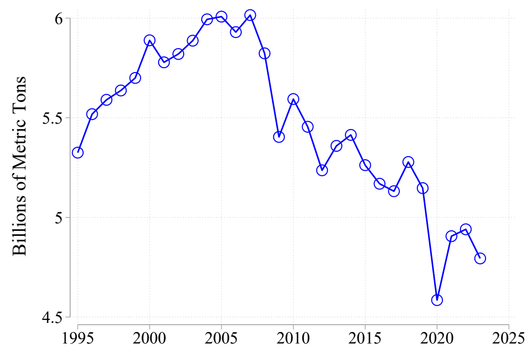
In the calculations that follow, the social cost of carbon acts as a sufficient statistic, embodying any assumptions or forecasts on the damage that emissions impose on output either directly (through lower productivity) or indirectly (through changes in production factors); how long these damages last (through carbon depreciation); and how future output is discounted. When calculating the social cost

[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.

Figure 1. Trends in U.S. 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 (2015). The right-hand figure plots carbon dioxide emissions in billions of metric tons. Data from 1995 to 2022.

of carbon, a key consideration is whether TFPE should capture the effect of inputs on the present value of *local* or *global* output. We explain that the social cost of carbon also embeds the degree to which society internalizes global damages from its emissions. An increase in domestic carbon emissions raises carbon in the atmosphere globally, and global emissions affect domestic productivity as well. We derive an expression for TFPE that nests both the case where only local or global externalities are internalized, as well as any case in between.

The true level of the social cost of carbon is by no means settled in the literature. We choose an agnostic approach: TFPE can be calculated for any cost of carbon, and we illustrate how the path of TFPE growth changes for alternative values from the literature. Much of the literature estimates the cost to be between \$50 and \$300 per ton of CO2. We show that even the top end of these estimates imply that the level-difference between TFP and TFPE is small (in the region of 1.5-10%), and the difference in the growth rate patterns is therefore minimal. That is particularly true for estimates that disregard global externalities (e.g., as advocated during the 2017–2021 Trump administration). If such estimates are correct, the macroeconomic implications of climate change are dwarfed by even the smallest productivity gains. Recent estimates of the social cost of carbon suggest, however, that damages might be much larger. Specifically, Bilal and Känzig (2024) find a social cost of carbon of \$923 in 2017 U.S. dollars per metric ton of carbon dioxide, based on global time-series regressions. This far exceeds traditional estimates in the literature. At the same time, even these estimates for the social cost of carbon assume that the costs of climate change are linear in temperature changes, making these estimates lower bounds if the cost of climate damage is convex. More broadly, they do not account for human costs of climate change, which could be of at least the same order of magnitude (Carleton et al. 2022).

We find that trends in TFPE growth differ markedly from trends in traditionally measured productivity growth if the social cost of carbon is as high as these recent estimates suggest. In advanced economies, there has been significant attention to the fact that TFP growth, while historically responsible for the majority of per capita output growth, has recently slowed down to levels well-below its long-term average. In the United States, for example, productivity growth has slowed to around 0.6% per year on average in the past two decades (Figure 1a). The decline in productivity growth happened at a time when U.S. emissions were falling (Figure 1b). These lower emissions increase TFPE growth by approximately 0.4 percentage points. In contrast, TFPE growth in the 1990s is lower than traditional TFP growth, as emissions were on the rise. Together, these adjustments yield a steadily increasing path of US TFPE growth—in sharp contrast to the productivity slowdown much discussed in the literature and policy debate. In particular, U.S. average TFPE growth since 2005 has exceeded growth in the 15 years prior. This pattern is not universal, but we document that for many countries, the slowdown is less pronounced when productivity is measured through TFPE.

In a broader cross-country comparison, we find that countries rank differently in growth when productivity is measured as TFPE. In Europe, service-intensive economies have significantly higher TFPE than TFP growth. In contrast, countries in Asia with high GDP growth rank lower in TFPE growth because they have seen large increases in carbon emissions. For China, emissions have risen at a sufficiently high rate to make recent average emissions-adjusted productivity growth deeply negative.

We also quantify the additional productivity gains that countries can achieve by reducing carbon emissions to net zero. In the framework, these potential gains are equal to the current ratio of carbon dioxide emissions over national output, multiplied by the social cost of carbon. For the United States, reducing emissions to net zero is equivalent to a productivity increase of 27% when using recent (high) estimates of the social cost of carbon. More broadly, we show that some of the countries with low TFPE growth have low carbon emissions to begin with. While this limits their ability to achieve further TFPE gains, these countries already cause limited climate damage.

Our TFPE estimates focus only on the damage caused by carbon dioxide. This is because the social cost of carbon has been extensively estimated, carbon emissions have the clearest link to temperature changes, and they have been central to the climate debate. The framework can be readily extended to include other greenhouse gases, using estimates for the social cost of those respective emissions. While our focus is on climate change, the framework can also be readily adopted to quantify the productivity-equivalent benefits of other forms of environmental progress through reduced pollution, such as improvements in air quality, in the spirit of Muller et al. (2011), for example.

Related Literature. This paper builds on and is closely aligned with the literature that incorporates climate damages into the analysis of macroeconomic growth. Our framework builds on the integrated assessment approach pioneered by Nordhaus (1977). A detailed review of this literature is provided in Nordhaus and Boyer (2003) and Hassler and Krusell (2018). Golosov et al. (2014) provide a modern general equilibrium model to analyze optimal taxation in a setting that combines non-renewable resources with climate damages.[2] A related literature explores how directed innovation in settings of endogenous technological change can combat climate damages. Acemoglu et al. (2012) embed climate damages in a framework with directed technological change and path dependence to understand the effectiveness of R&D subsidies and carbon taxes. Acemoglu et al. (2016) provide a quantitative assessment of climate damages during a green transition with a focus on how policy affects competition

[2]A related literature studies the effect of the depletion of exhaustible resources, like fossil fuels, on growth and optimal policy. Dasgupta and Heal (1974) is an early model of non-renewable resources, while Stokey (1998) formalizes the idea that non-renewable resources may create bounds on growth.

between polluting and non-polluting technologies.[3] Our contribution to this literature is to provide an easily measurable macroeconomic metric of productivity that is conceptually consistent with the aforementioned canonical models of macroeconomics and climate.

Perhaps closest to ours are papers that propose introducing "green accounting" to national accounts. This literature builds on the insight of Weitzman (1976) that, although an economy's net national product (national output measured net of capital depreciation) is a static measure of output, it nonetheless captures the dynamic, intertemporal welfare in a dynamic competitive economy. Formally, Weitzman shows that a constant consumption path equal to the current net national product generates the same welfare as the equilibrium consumption path. The logic is that the competitive price of capital investment goods captures the value of future consumption goods that they deliver. In principle, this logic extends to carbon emissions, in the sense that they deplete the stock of "environmental capital", thus lowering future consumption (see, e.g., Weitzman and Löfgren 1997). Thus, some function of carbon emissions should be subtracted from national income to obtain a welfare-relevant measure of output. Nordhaus (2021) summarizes this idea, labeling the remainder of national income Green GDP. We show that TFPE, in addition to being the welfare-relevant measure of productivity in integrated assessment models, is the relevant measure of productivity corresponding to Green GDP.

A related but distinct strand of research seeks to adjust GDP or productivity growth for environmental factors treating the environment as an input into production. Notably, the OECD has previously estimated Environment-Adjusted Total Factor Productivity for 1996-2018 (Rodríguez et al. 2018).[4] While we share the high-level motivation of constructing economic aggregates that account for environmental damage, the approach is conceptually different.[5] The OECD's measure addresses the question: what would the growth rate of GDP or TFP be at each point in time if environmental damage had remained unchanged since the previous period? This differs from our proposal in a number of ways. Primarily, our measure of TFPE is dynamic in the spirit of Weitzman (1976): it captures the economy's ability to convert a bundle of inputs into consumption, taking the long shadow of today's emissions on future output into account. The OECD's metric, instead, is static. Additionally, the OECD's measure treats pollution as an input into production, and relies on constant pollution output elasticity estimates across the sample period. Besides the 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 by-product of production, and only requires data on traditionally-measured productivity growth, emissions, GDP and an estimate of

[3] 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.

[4] 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, which is the opposite of what we find for TFPE.

[5] The correlation between TFPE growth and EATFP growth for the overlapping sample in the main specification is 0.38.

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 conceptual difficulty.[6]

Our finding of a gradual acceleration in U.S.' TFPE growth offers a more optimistic perspective on recent trends in aggregate productivity growth. 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 productivity is measured as the economy's ability to transform input bundles into the present value of output, taking global climate damages into account, and when the cost of carbon is as high as some of the recent estimates suggest, the slowdown is milder and, in some cases, reversed. Conversely, we find that if the social cost of carbon falls in the range of the previous consensus, then the economic fallout from climate change is small relative to economic consequences of slightly higher productivity growth.

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 both consumption per capita and population growth into account. Basu et al. (2022) discuss 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. In similar spirit, Rachel (2021) shows that an increase in leisure-enhancing technological progress reduces growth in traditional measures of TFP growth.

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

2. Framework

This section introduces the framework used to derive emissions-adjusted total factor productivity (TFPE). Section 2.1 first describes the environment. Section 2.2 and 2.3 derive TFPE and discusses the distinction between local and global climate damages and the associated cost of carbon. Finally, Section 2.4 explains why TFPE is a welfare-relevant measure of productivity.

[6] 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.

2.1. Environment

The production side of the economy is consistent with canonical models in the macro-climate literature. Production capacity is a function of production factors, productivity, and climate. Following the functional form proposed by Nordhaus (1992), an economy's output Y_t at time t is given by

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

where $A_t F_t(\mathbb{K}_t)$ denotes the economy's output absent climate damages and S_t is the stock of past carbon emissions in the atmosphere. The production function $F(\cdot)$ is neoclassical for a vector of production factors $\mathbb{K}_t$. The stock of emissions S_t is determined by the full history of emissions between the pre-industrial era and time t, in all economies across the globe. The differentiable function $D(\cdot)$ records the damage caused by the stock of carbon. We do not impose functional form assumptions on the damage function and on the function that governs how past emissions accumulate and depreciate in the atmosphere.

Emissions themselves are a byproduct of production and are assumed to be given by

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

where ϕ_t is time-varying to reflect the fact that structural changes such as the combination of inputs, sectoral allocations or production technologies may alter the amount of carbon that a given input bundle emits. This emissions function nests the specification in Nordhaus (1992).

2.2. Productivity

What is the relevant measure of productivity in this environment? Tradditional measures of TFP captures the rate at which bundles of inputs can be converted into aggregate output, that is

$$TFP_t \equiv \frac{\partial Y_t}{\partial F_t(\mathbb{K}_t)} = A_t D(S_t). \tag{3}$$

This is a useful measure because it closely relates to consumption and welfare. Weitzman (1976) shows that aggregate net output equals the annuity value of discounted current and future consumption.[7] Productivity along (3) then has clear welfare relevance.

If production comes with emissions, however, traditional productivity measures are not obviously welfare relevant. There are two primary concerns. First, emissions cause climate damages that cast a long shadow on productive capacity. In an economy where agents are forward looking, a welfare-relevant measure of productivity should take those long-term effects into account. Second, climate damages are global, as the stock of carbon in the atmosphere is the result of emissions across territories. In climate policy evaluations these global externalities are typically taken into account. If agents internalize these externalities too, a welfare-relevant measure of productivity accounts for the marginal impact of a bundle of inputs on future output across the globe.

[7] We discuss the conditions under which Weitzman (1976)'s interpretation of output holds in Section 2.4.

To address both concerns, we define emissions-adjusted total factor productivity (TFPE) as the marginal effect of a bundle of inputs on the present value of output, taking climate damages into account. Output here can be defined either globally, if agents fully internalize their externality, or locally in case they do not. The counterpart for traditional productivity in equation (3) is

$$TFPE_t \equiv \frac{\partial \boldsymbol{U}_t}{\partial F_t(\mathbb{K}_t)}, \tag{4}$$

where $\boldsymbol{U}_t$ in the numerator is the present value of output:

$$\boldsymbol{U}_t = \mathbb{E}_t \sum_{s=0}^{\infty} \left(\prod_{k=t}^{t+s} \beta_k Y^*_{t+s}(D(S_{t+s})) \right), \tag{5}$$

where, in turn, $\mathbb{E}_t$ is the expectations operator and where β_t is the (possibly stochastic) discount rate.[8]

Output Y^*_t in equation (5) is either equal to domestic output, in which case TFPE for a particular country ignores the damages that carbon emissions cause elsewhere, global output, so that TFPE fully recognizes the global nature of carbon damages, or a convex combination of the two. The choice of which output to include is akin to choosing whether assessments of climate policies internalize a country's global or domestic externalities. For small countries this distinction is especially important, as the domestic cost of their climate damages is limited. As we show below, when we calculate TFPE, the social cost of carbon will capture the extent to which domestic or global output is included in Y^*_t.

Inserting the (5) into (4) yields the following expression for TFPE:

$$TFPE_t \equiv \frac{\partial \boldsymbol{U}_t}{\partial F_t(\mathbb{K}_t)} = A_t D(S_t) \quad + \quad \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \frac{\partial Y^*_{t+s}(D(S_{t+s}))}{\partial F_t(\mathbb{K}_t))}. \tag{6}$$

Thus, emissions-adjusted productivity is equal to the sum of traditionally measured productivity and an adjustment term that represents the present value of the marginal change in the present value of future output as a result of raising the quantity of input bundles $F(\mathbb{K}_t)$.

2.3. TFPE and the Social Cost of Carbon

It may seem that TFPE can only be calculated with knowledge of the damage function and the production function, on which we made few assumptions, because of the derivative in the final term of equation (6). We next show, however, that this adjustment term can be written as a simple function of emissions, domestic output, and the textbook definition of the social cost of carbon, the latter being a routinely estimated object in the literature. This takes two steps. First rewrite the adjustment term as a function of emissions rather than the production function by inverting the emissions equation (2):

$$\mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \frac{\partial Y^*_{t+s}(D(S_{t+s}))}{\partial F_t(\mathbb{K}_t)} = \phi_t \mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \frac{\partial Y^*_{t+s}(D(S_{t+s}))}{\partial E_t}. \tag{7}$$

[8] Alternatively, TFPE can be calculated along (3) but using a measure of output that subtracts the present value of climate damages. In Section 2.4 we explain that this "green GDP" approach to national account yields the same expression for emissions-adjusted total factor productivity.

Thus, the term on the right hand side is a product of the carbon intensity of production ϕ_t and a discounted infinite sum of damages due to the marginal unit of emissions.

The second step involves showing that the summation term in (7) has a natural interpretation: it is the present value of the marginal damage to future output that is induced by an additional unit of emissions. This is known as the Cost of Carbon (CC) in the literature that combines the analysis of climate and the macroeconomy (see, e.g., Hassler et al. 2016). Formally, we can write:

$$\mathbb{E}_t \sum_{s=0}^{\infty} \beta^s \frac{\partial Y^*_{t+s}(D(S_{t+s}))}{\partial E_t} = \frac{\partial \boldsymbol{U}_t}{\partial E_t} = -CC_t.$$

Although the cost of carbon is not observable, it is widely estimated in the literature, as it determines optimal Pigouvian carbon taxes. Inserting this into our expression for TFPE, we get

$$TFPE_t \equiv \frac{\partial \boldsymbol{U}_t}{\partial F_t(\mathbb{K}_t)} = A_t D(S_t) - \phi_t \cdot (CC_t)\,. \tag{8}$$

Finally, we can use (1) to write the emissions intensity of domestic production, ϕ_t, in terms of TFP, carbon emissions, and GDP: $A_t D(S_t) \frac{E_t}{Y_t}$. In other words, the carbon intensity of production is simply the product of traditionally-measured TFP and the ratio of carbon emissions to GDP. Inserting this definition into the expression for TFPE (6) we obtain:

$$TFPE_t = TFP_t \cdot \left(1 - \frac{E_t}{Y_t} CC_t\right). \tag{9}$$

It follows that to measure emissions-adjusted total factor productivity, only four objects are needed. Two are observable in publicly available datasets (emissions and GDP), while the other are routinely estimated (TFP and the cost of carbon).

By calculating TFPE along (9), the estimates inherit assumptions on the discount rate and the degree to which global damages are internalized from the estimate of the cost of carbon. The parsimony of the expression means that researchers with a particular assessment of the cost of carbon can readily devise those estimates to obtain a consistent series of TFPE. In the quantitative sections of the paper, we use estimates of the cost of carbon that assume full internalization of global damages. This is also known as the social cost of carbon (SCC), which is most frequently used in policy evaluations (Stern et al. 2022, National Academies of Sciences, Engineering, and Medicine 2017). It is equally possible, however, to use estimates of the cost of carbon that focus solely on domestic economic costs of emissions, sometimes referred to as the domestic cost of carbon (DCC). This was the approach used to evaluate climate policy in the United States between 2017 and 2021 (Voosen 2021). In the framework, this is achieved by setting $Y^*_t = Y_t$ at a country level.

2.4. Welfare relevance

We have thus far derived TFPE as a relevant productivity measure in a setting that is consistent with canonical integrated assessment models. It might seem unintuitive, however, to define productivity as the marginal effect of inputs on the *present value* of output. In the remainder of this section, we draw on the "green accounting" literature, which seeks to incorporate climate damage into national accounts, to show that the focus on the present value is appropriate in a dynamic setting.

Defining TFPE as the marginal effect of a bundle of inputs on the present value of production, rather than production today, builds on the literature on the welfare-relevance of economic aggregates after Weitzman (1976). He explains that national output, if measured as the sum of consumption and 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, Weitzman shows that for constant 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 the welfare attained in the competitive equilibrium with no externalities. The idea underlying this result is that competitively set investment good prices reflect their value in the production of future consumption goods.

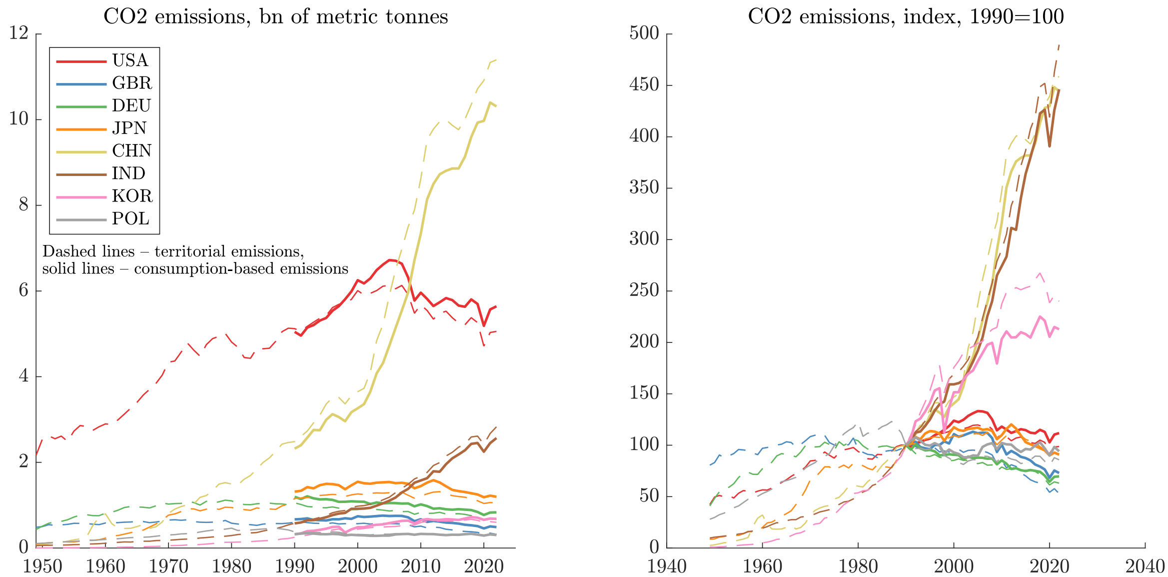
The logic carries through from measures of output to measures of productivity. Thus, if we define output correctly, then the TFP measured in a standard way already captures the economy's ability to transform bundles of inputs into the present value of consumption, and so is the right concept to look at from a welfare standpoint. However, in reality output is not defined correctly: it is a gross measure that includes depreciation, and even if depreciation was excluded, climate externalities mean that the observed price of natural capital is either non-existent or too low. For these reasons, TFP as measured by the statistical agencies worldwide overlooks climate damages that are associated with production, thus overestimating true, welfare relevant productivity.

The green accounting literature builds on Weitzman (1976)'s seminal contribution, by advocating that climate damages should be subtracted from national income (see, e.g., Weitzman and Löfgren 1997). The idea is 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 Appendix A we show that, at the global level, TFPE measures total factor productivity correctly, because the social cost of carbon is, by its definition, the correct price of the (negative) investment in the natural environment caused by carbon emissions. Thus, while green national accounts offer a complementary way to analyse the macroeconomic effect of climate change to integrated assessment models, our measure of TFPE is the relevant measure of productivity in both setups.

3. Quantification

To calculate emissions-adjusted total factor productivity using equation (9), we need data on four variables: carbon emissions, real output, traditionally measured productivity, and an estimate of the social cost of carbon. The first three are readily available in publicly available cross-country datasets, and we summarize our data sources in Section 3.1. The social cost of carbon has been extensively estimated in the literature, and we justify the two values that we use throughout the analysis in Section 3.2.

Figure 2. Carbon Dioxide Emissions in Selected Economies



Notes: This figure plots the path of annual territorial and consumption-based CO_2 emissions from the Global Carbon Project (Andrew and Peters 2024). The left-hand figure pots emissions in billions of metric tons across selected countries, the right-hand figure plots an index of emissions using 1990 as the base year.

3.1. Observable variables

To measure carbon emissions, we rely on annual consumption-based CO_2 emissions from the Global Carbon Project (Andrew and Peters 2024). These are available from 1990 to 2022 for a large set of countries. The consumption-based emissions series attribute carbon emissions, generated in production, to the country where goods are consumed rather than where they are produced. We complement these series with data on territorial emissions, which attribute all emissions to the location of production. Data on territorial emissions are available for longer time horizons and allow us to extend the analysis to 1950. Using consumption-based emissions as the primary series ensures that we do not overestimate TFPE growth for countries where carbon emissions in production are outsourced to other countries. Figure 2 plots emissions for selected countries.

Data on traditionally measured productivity growth across advanced economies, as well as GDP, comes from the Penn World Tables (edition 10.01, see Feenstra et al. 2015). We also use PPP GDP per capita to analyze how TFPE growth evolves along the development path.[9]

3.2. Social cost of carbon

Besides these observables, we need an estimate of the cost of carbon to calculate TFPE. For the remainder of the paper, we focus on the measure of TFPE that fully internalizes the global climate externality. This approach uses the *social* – rather than the domestic – cost of carbon. This choice is motivated by the observation that when the TFPE measurement assumes that only country-level damages are

[9]Note that these series do not account for capital utilization. For the United States, we could use utilization-adjusted series (Fernald 2015), but, given the long-term similarity in growth between utilization-adjusted and unadjusted series, we prefer to harmonize data sources across countries.

internalized ($\lambda = 0$), the TFPE estimates imply a minimal adjustment to TFP even for the largest and most polluting economies, and negligible adjustments for all others. This renders calculations under the $\lambda = 0$ assumption unnecessary. More generally, the focus on $\lambda = 1$ is consistent with the global nature of the climate challenge and aligns with how climate challenge is evaluated in the context of international cooperation.

There is a rapidly evolving literature that estimates the SCC and the validity of both methodologies and results remains the subject of a rich academic debate. We aim to sidestep those controversies in this paper by providing two series for TFPE, corresponding to two different estimates of the SCC that represent two views in the literature. We discuss these two estimates momentarily. However, given the parsimony of our TFPE methodology, it is straightforward to derive alternative TFPE series based on different estimates. We express the social cost of carbon in 2017 U.S. dollars.

Our main series for TFPE are based on estimates of the SCC of Bilal and Känzig (2024). Their estimates suggest the SCC of \$923 in 2017 (expressed in 2017 dollars), which is around 6 times greater than many previous estimates in the literature. Bilal and Känzig follow a large literature that estimates the SCC by estimating the response of economic activity to variation in weather. The estimated sensitivities are then used to calibrate an integrated assessment model, usually of forms consistent with our framework, which offer the structure to inform calculations of the SCC.[10] Contrary to the literature, Bilal and Känzig estimate the effect of global temperature on global output, instead of the effect of local temperature on local output. They explain that estimates based on local variation underestimate the true effect of climate on economic activity, because global shocks are more likely to capture the positive correlaton between rising temperature and extreme weather events. Bilal and Känzig (2024) find that a 1°C increase in temperature reduces global output by 12%. Embedding this elasticity in a general equilibrium model based on Nordhaus (1992), with a discount rate 2%, they arrive at the current level of \$1367 SCC, which translates to a \$928 in 2017 (and expressed in 2017 U.S. dollars).

To highlight the effect of altering the SCC estimates on TFPE, we present an alternative series that relies on the preferred SSC estimate from an extensive meta analysis. Based on 1,823 estimates in 147 studies between 2000 and 2020, Moore et al. (2024) propose a social cost of carbon of \$252 per ton in 2017 US dollars. To arrive at this proposal, they combine the raw SCC estimates with weights assigned by an expert survey. This survey involves detailed questions about the proper modeling approaches, damage assessments, and discount rates. They then train a random forest model to produce a synthetic distribution of estimates weighted to match expert recommendations. The resulting distribution of the weighted average of the SCC estimates is \$252.

Taken together, these two estimates of the SCC cover a wide range of possibilities, reflecting the frontier of our understanding of climate damages. Nonetheless, significant two-sided uncertainty remains even with respect to this wide range. There are estimates of the SCC that fall substantially below the lower of the two estimates, some of which have been used by governments to guide policy—for example, during Donald Trump's first term as U.S. President. However, as we will show below, under these estimates, the implied difference between the growth rates of TFP and TFPE is minimal. On the

[10] Dell et al. (2014) provide an excellent survey of this approach.

upside, the social cost of carbon that we focus on restricts attention to the damages that are within the economic realm. Accounting for damages more broadly, e.g., those related to the loss of health, heightened uncertainty due to weather extremes, loss of biodiversity, animal welfare considerations, etc., would further raise the estimate of damages.

To compute TFPE over time along equation (9), we require the entire time path of the SCC_t, and not just its value at a given point in time. The social cost of carbon changes over time for two reasons. First, economic growth means that climate damages spread over a larger economic pie, increasing the dollar value of the losses. Second, the marginal damage of a metric ton of carbon might itself be time-varying. While there is a large literature that estimates the level of the SCC, there is less emphasis on its growth rate. Our approach is to compute the average SCC growth rate implied by a sample of important studies of the SCC. As part of this sample, we collect the SCC estimates reported in Nordhaus (2017), as well as those maintained in the Resources for the Future Database (Prest et al. 2022). In total, we computed the growth rates in 14 models at different points in time. We find little variation in the implied growth rates of the SCC across time (i.e., within a given model, the SCC grows at a roughly constant exponential rate) but substantial heterogeneity across models. The median growth rate of the SCC across these models is 2.1% p.a., and the corresponding mean is 2.6%.[11] To reflect these considerations, in our calculations we assume the growth rate of the SCC of 2.1% per year.

4. Results

In this section, we present our main results. We start by presenting the TFPE growth series and comparing trends in TFPE growth with those in traditionally measured TFP growth. We then study the levels of TFP and TFPE and the gap between them. Our focus is on the period from 1990 to 2019, as this period provides data on TFP and consumption-based emissions for a wide range of countries.

4.1. Trends in TFP(E) growth

Our headline results for the United States are shown in Figure 3, which plots the smoothed trajectory of U.S. TFP and TFPE growth. Traditionally measured TFP growth exhibits a familiar pattern: it 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).

Our first key result is that, when the social cost of carbon is calibrated to the lower value of around \$252, the quantitative impact of accounting for climate damages is small: the TFP-TFPE growth differences rarely exceed 0.1 percentage points per year, and the broad patterns described above remain unaltered. This result is interesting, since it puts into perspective the importance of economic damage of climate change relative to gains from productivity growth. The takeaway is that, for the social cost of

[11] We find close to no correlation between the level of the SCC and its growth rate across models.

Figure 3. TFP and TFPE Growth for the United States

Notes: The figure plots the path of TFP and TFPE for the United States between 1990 and 2023. Each series is smoothed using a 5-period centered moving average to mitigate cyclical variation. Growth is given by the percentage change in TFPE along equation 9. The TFP series comes from the latest edition of the Penn World Tables.

carbon that reflects the recent consensus, global economic costs of emissions would be overwhelmed by even minor improvements in productivity.[12]

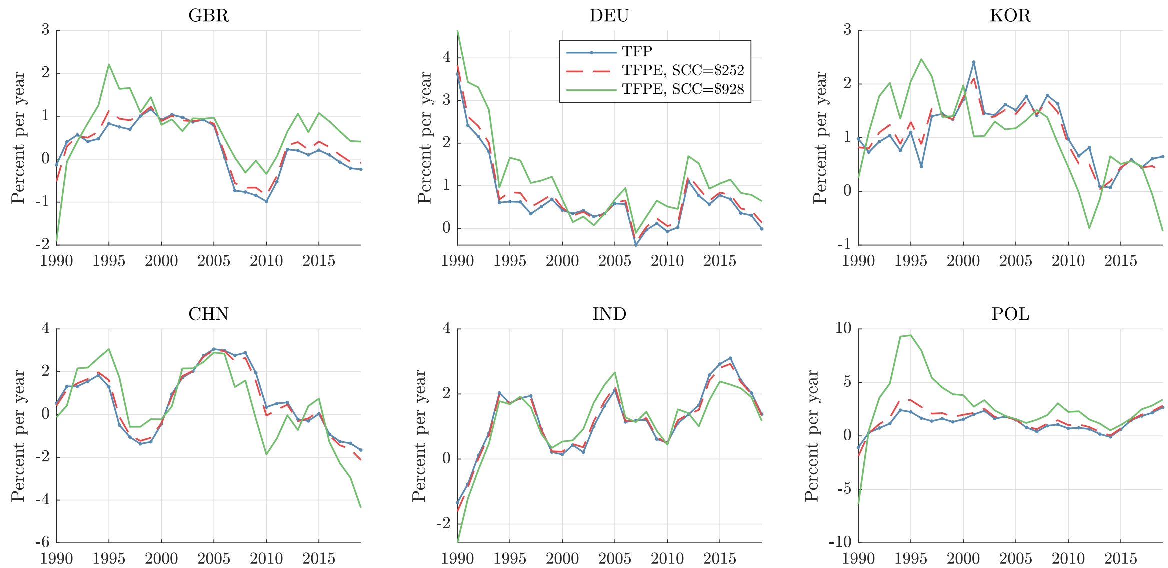
The results change significantly if the SCC is set to a value of $928, in line with the latest econometric evidence. TFPE growth during the 1990s and early 2000s is notably low, remaining well below the TFP growth observed in the earlier part of our sample. The crossover point occurs around 2005, coinciding with the widely discussed timing of the United States' economy 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 the traditional TFP series disappears.

Figure 4 provides similar figures for selected economies to show that patterns in TFP and TFPE growth differ significantly. Note that the vertical axes differ in each sub-figure. For the United Kingdom and Germany, TFPE growth is persistently higher than TFP growth. This illustrates that these countries have had a persistent decline in the ratio of carbon emissions to national income. Productivity growth in both countries has been similar after the Global Financial Crisis to that of productivity growth between 2000 and 2005. A very different pattern emerges in Korea and China. As seen in Figure 2, these countries have seen a strong increase in their carbon emissions over the past two decades. The climate damage caused by this is sufficiently large to cause productivity growth to be negative for most years since 2010 in Korea and for most years since 2015 in China. India's productivity growth steadily increases even when climate damages are taken into account, which likely reflects the service-intensity of its recent growth (Fan et al. 2023). Poland experienced significant TFPE growth as it reduced its emissions relative to GDP in the 1990s and has had steady TFP and TFPE growth in subsequent years.

We now expand our analysis to a large number of countries in Figure 5, which 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

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

Figure 4. TFP and TFPE Growth in Selected Economies



Notes: Each panel shows average annual growth of TFP (blue bars) and TFPE (at a social cost of carbon of $928, green bars, or $252, stars). From left to right, the panels present data for the United States, United Kingdom, Germany and Japan. TFPE is calculated using equation 9. The TFP series comes from the latest edition of the Penn World Tables.

years post-2005.[13] The figure shows that countries with high rates of TFP growth typically also had high rates of TFPE growth between 1990 and 2005. That is less the case in recent years: from 2005 to 2019, countries are further away from the 45-degree line—the point at which TFP rank equals TFPE rank—in the right-hand figure than in the left-hand figure. Countries above the line rank higher in TFPE than in TFP growth, while countries below the dashed line rank lower in TFPE than in TFP growth.

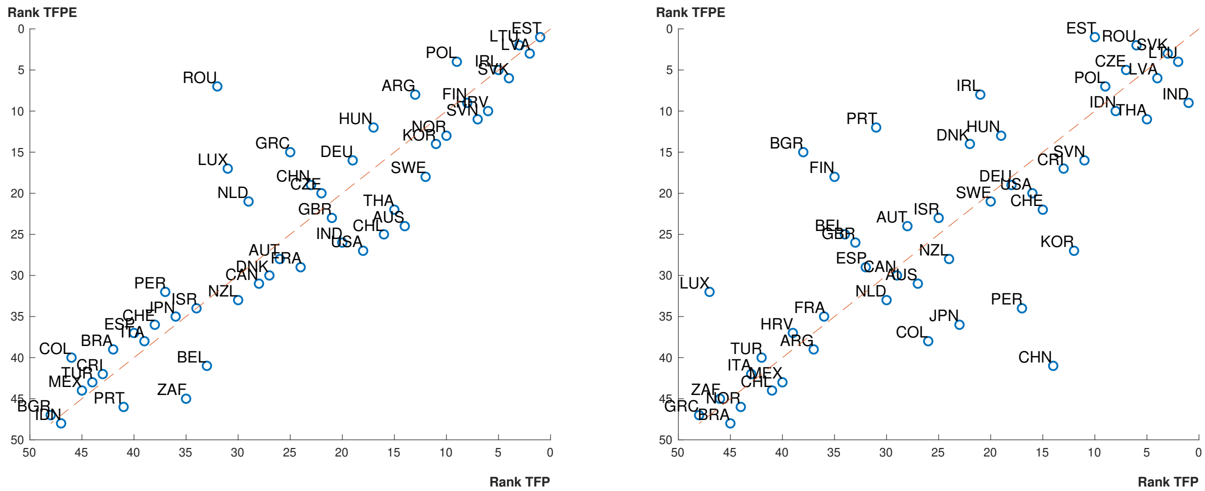
In the earlier years of the data, there are some geographical patterns in the countries for which TFPE growth exceeds or falls short of TFP growth. Former member states of the Soviet block such as Romania, Poland and Hungary are all among the countries with a high TFPE rank, reflecting that their emissions did not rise as much as in other countries with similar levels of productivity growth. Most prominently, however, there is a strong correlation between TFP and TFPE growth in these years.

That is no longer the case in the right-hand figure: TFPE growth appears decoupled from TFP, with 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. We conclude that taking account of progress in terms of reducing pollution can significantly change a country's growth standing.

Figure 6 compares the change in TFPE growth in the period after 2005 and the period prior to 2005, to asses the degree to which cross-country differences in productivity trends extend to TFPE. The figure plots the change in TFPE on the vertical axis, and the change in TFP on the horizontal axis. The 45-degree line helps visualize whether TFPE changes outpace TFP changes, with points above the line indicating stronger relative TFPE performance relative to TFP.

[13] The raw data across countries are presented in Table A1 in the Appendix.

Figure 5. Comparison of Country Rank for TFP and TFPE Growth

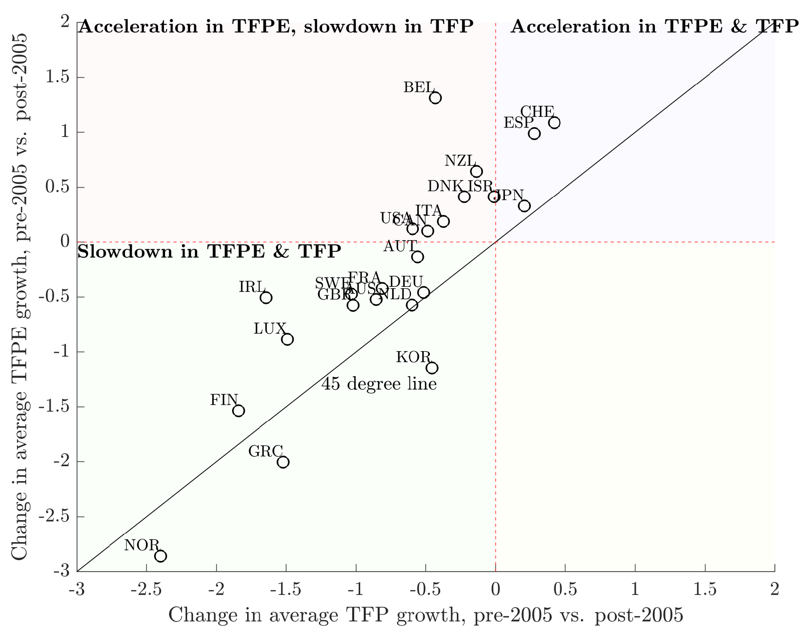


(a) Average for 1990-2005 (b) Average for 2005-2019

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 figure assumes SCC=$928 in 2017. Growth is given by the percentage change in TFPE along equation (9). Traditionally measured TFP growth is obtained from the Penn World Table. The dashed-red reference line is 45 degrees.

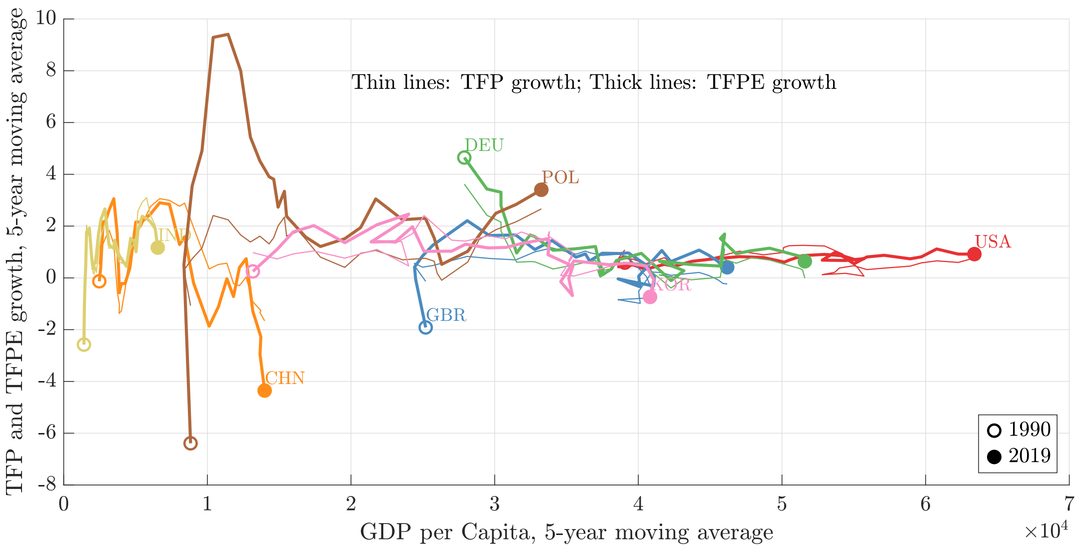
The figure reveals that there are several countries for which TFPE growth has accelerated even as traditionally measured productivity growth slowed down – the pattern we have previously documented for the US. These are the countries in the top-left quadrant of the figure. Among these are Belgium, Denmark, Israel, New Zealand, Canada, and Italy.

Figure 6. Acceleration and slowdown in long averages of TFP and TFPE growth



Notes: The figure plots, for each country depicted, on the x-axis: 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 y-axis the equivalent difference but in TFPE space, under the assumption of a social cost of carbon of around $928. The TFP data come from the latest edition of the Penn World Tables.

Figure 7. TFP and TFPE growth rates along the development path



Notes: The figure plots GDP per capita, measured in PPP 2017 US 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 Tables.]

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, only South Korea, Greece and Norway experienced TFPE growth slowing down more than TFP growth.

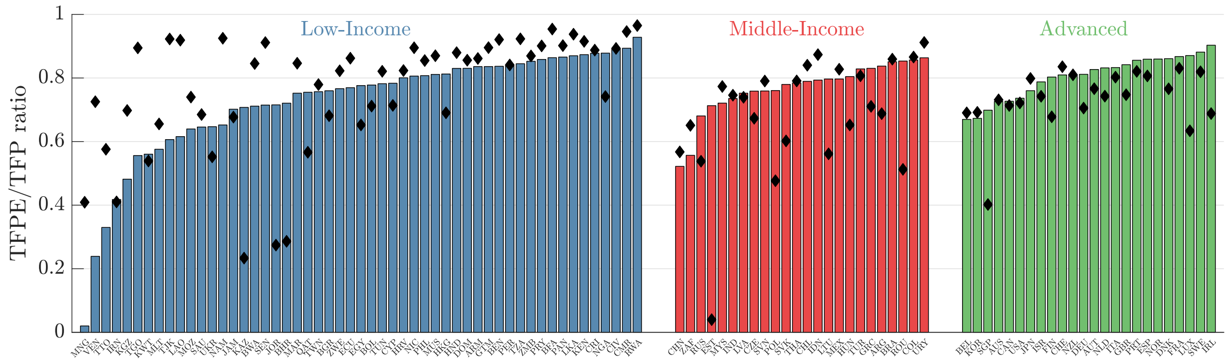
4.2. TFPE along the development path

Having previously analyzed the trajectory of TFPE over time, we next present how TFPE growth evolves along the development path and how this differs from the path of TFP. Figure 7 plots a 5-year moving average of productivity 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 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.[14] 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 economy 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.

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

Figure 8. The level gap between TFP and TFPE



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

In comparison to the emerging markets, frontier economies 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 because emissions started declining in earlier years in these countries, and also because US remains richer than these countries in terms of per-capita income.

4.3. The gap between TFP and TFPE

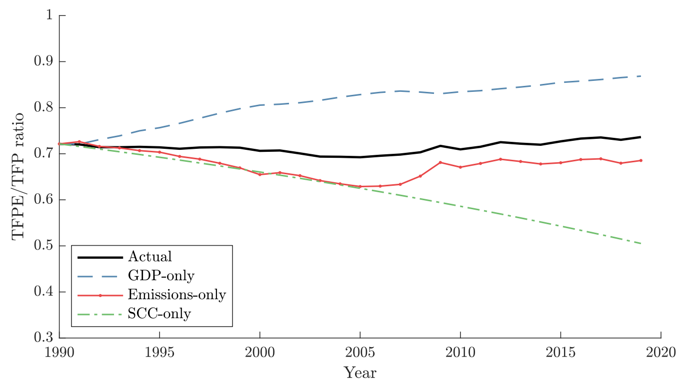
The preceding analysis has exclusively focused on trends in the growth of TFPE. While growth in TFPE quantifies the productivity gains from reduction in emission intensity of a country's production, it masks the fact that countries may have lower emissions intensity to begin with.

Figure 8 addresses this by graphing the ratio of TFP and TFPE in levels. The vertical axis plots the ratio between both productivity measures, which equals $(1 - [E_t/Y_t] \cdot CC_t)$ (see equation 10). This ratio equals 1 for an economy without emissions and 0 for an economy where emissions cause damages equal to today's GDP (note that this ratio can in principle be negative, which occurs when the value of global damages from emissions in a particular country is greater than the value of goods and services this country produces). Bars present the ratio of TFPE over TFP in 2019, diamonds give the ratio for 1990. This ratio provides insight into the potential gains from achieving net zero:, reaching net zero would raise the level of TFPE to match that of TFP, bringing the bars all the way to 1, and in the process resulting in a higher growth rate for TFPE relative to TFP.[15] In other words, the size of the gap between the ratio and 1 reflects the potential differential between the growth rates of TFPE and TFP as economies transition to less emissions-intensive production. By the same token, of course, the size of this gap measures the degree to which a country is polluting (relative to its size) and thus degrading the global climate.

The figure shows that TFPE growth alone is not a sufficient yardstick for a country's emissions-adjusted economic performance. The level of TFPE versus TFP contains much more information on

[15] Of course, all else may not remain equal—the transition to net zero could involve costs as well as opportunities that might causally affect TFP growth.

Figure 9. The Wedge between TFPE and TFP and Counterfactuals in the United States



Notes: The figure plots the $\frac{TFPE_t}{TFP_t} = 1 - E_t \cdot \frac{SCC_t}{\hat{Y}_t}$ ratio (see equation (9)) in levels in thick black lines, as well as 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 red lines plot the TFPE/TFP ratio across countries 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 PWT.

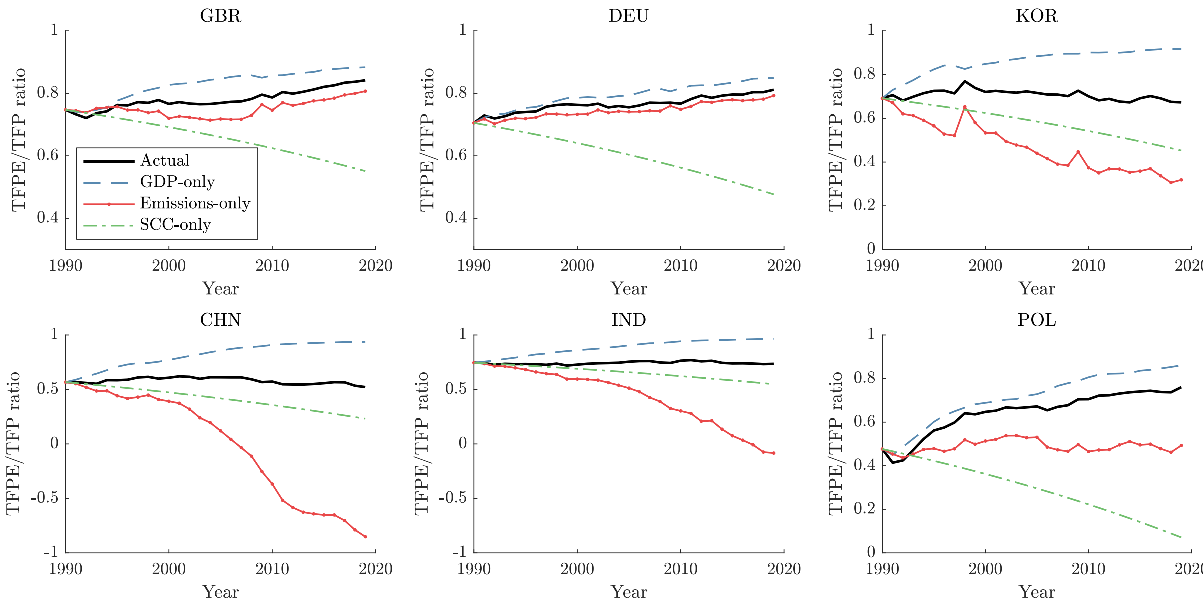
the current damage an economy is doing to the climate, and TFPE growth in countries with low initial TFPE over TFP ratios can naturally be higher than in a country where emissions are already low. Among the high-income group, for example, countries like Portugal, Spain, France and Sweden had TFPE over 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 further TFPE growth is relatively limited.

A number of other results stand out. First, the figure confirms that there is no clear relationship between income and the ratio of TFPE and TFP. This echos the lack of an income-TFPE growth relationship in Figure 7. Second, While the level of TFPE-TFP gap seems broadly uncorrelated with development status, there is a clear pattern across these three groups in cumulative change, as indicated by the difference between diamonds (1990) and bars (2019). Over these 30 years, most of the poor nations recorded significant declines in TFPE-TFP ratio, while most of the advanced economies recorded improvement. Third, 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.

4.4. Decomposition of TFPE Growth

As a final empirical analysis, we analyze the drivers of TFPE growth by decomposing growth in the ratio of TFPE over TFP into changes coming from emissions, national output, and the social cost of carbon. To do so, we use the definition of TFPE in in equation (9), and present results for the United States and the selected economies in Figure 4. Figure 9 presents the decomposition for the United States, while results for the other economies are presented in Figure 10. The vertical axes again presents the ratio

Figure 10. The Wedge between TFPE and TFP and Counterfactuals in Selected Economies



Notes: The plot decomposes the ratio of TFPE over TFP for selected economies. See the notes for Figure 9 for more details.

of TFPE over TFP. For the United States, the ratio is just above 0.7 in 1990, which means that the U.S. economy was 30% less productive once the present value of climate damages are taken into account. The 1990 ratio is similar for the United Kingdom, Germany and Korea, but substantially lower for China and Poland.

The lines in the figures provide counterfactual for alternative paths of the variables that jointly drive the ratio of TFPE over TFP. The black-solid line gives the overall trajectory for the TFPE over TFP ratio. The red-circled line gives the path of the TFPE over TFP ratio of emissions evolve in the way that they empirically have, holding the social cost of carbon and national output at their 1990 levels. The blue-dashed and green dash-dotted line perform a similar exercise plotting the path of TFPE growth if, respectively, only national output or the cost of carbon had evolved, holding other variables constant.

The figure shows that in the United States, the effect of the rise in GDP and the rise in the social cost of carbon are of a similar magnitude, 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), 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 UK 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 value of its emissions measured with the 1990 SCC exceeded its GDP in 1990 by nearly twofold.

5. Conclusion

This paper proposes a new measure of productivity, TFPE, that adjusts for the climate damage induced by CO2 emissions. TFPE measures the economy's ability to transform bundles of inputs into units of present-value output, taking the long shadow of emissions on future production into account. 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 simple to calculate under modest assumptions: researchers only need an estimate of the social cost of carbon, as well as data on carbon emissions, real GDP, and traditionally measured productivity growth. We hope this metric will prove to be a useful yardstick against which to compare economic performance across countries and over time.

We find that both trends and relative country performance differ significantly between TFPE and traditional measures of total factor productivity. For the United States, we find that TFPE has slightly increased since the mid-2000s, provided that recent (high) estimates of the social cost of carbon are used in the calculation. This increase is driven by a significant reduction in carbon emissions: consumption-based 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 fact that traditional measures of productivity have significantly slowed down in recent years. 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 deeply negative in recent years.

The framework we propose offers various avenues for future research. Our estimates align with the broader climate economics literature that focuses on the economic damages of carbon emissions. Other greenhouse gases can also be readily incorporated into the analysis. Nonetheless, it is increasingly well understood that climate change has far-reaching consequences that extend beyond the production boundary. The proposed framework can be straightforwardly extended to account for negative effects of emissions beyond their direct impact on climate. Future research building on this methodology could expand the notion of damages to encompass the environmental, biological, and other broader costs of climate change.

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Appendix A. TFPE and green accounting

In this appendix, we first review the insight of Weitzman (1976), which states that, under specific —-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: L is (constant) labor, N is a stock of natural (environmental) capital, E is emissions which we assume is the same as 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 natural environment.

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

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

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

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 is the optimality condition for natural capital – can be rewritten as $r = \frac{\partial Y/\partial N}{\mu} + \frac{\dot{\mu}}{\mu}$: 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 CE welfare:

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

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 CE equation above and the envelope theorem. Thus:

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

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 reflects 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

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

where L is (constant) labour, A is constant productivity term, N is a stock of natural capital, S is the stock of CO2, $\bar{S}$ is the pre-industrial stock of CO2, $D(\cdot)$ is a damage function, with $D' > 0$. Then

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

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

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

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

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 TFPP

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:

$$TFP := \frac{\partial Y(t)}{\partial L(t)} = AD(N(t)).$$

The fact though is that the way we traditionally measure productivity is with GDP. TFP estimated by statistical agencies worldwide is, in terms of the variables defined in the model here, given by:

$$TFP_{real\ world}(t) = \frac{\partial C(t)}{\partial L(t)} = \frac{\partial(Y+\mu E)}{\partial L} = \frac{\partial Y}{\partial L} + \mu\frac{\partial E}{\partial L} = \frac{\partial Y}{\partial L}(t) + \mu(t)\phi(t)$$

where $\phi(t)$ is as we defined it: $E(t) = \phi(t)L(t)$. Thus this real world TFP measure overestimates the welfare-relevant TFP by not subtracting the value of emissions that the economy generates.

TFPE: We define TFPE as an intertemporal version of TFP:

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

This shows that TFPE is indeed the welfare relevant measure of productivity. Thus, our framework is 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. Additional Tables and Figures

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	
		TFPE	TFPE		TFPE	TFPE	TFPE vs. TFP		TFPE vs. TFP	
	TFP	(SCC = 252)	(SCC = 928)	TFP	(SCC $252)	(SCC = 928)	(SCC = 252)	(SCC = 928)	(SCC = 252)	(SCC = 928)
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 (SCC = 252)	TFPE (SCC = 928)	TFP	TFPE (SCC $252)	TFPE (SCC = 928)	TFPE vs. TFP (SCC = 252)	TFPE vs. TFP (SCC = 928)	TFPE vs. TFP (SCC = 252)	TFPE vs. TFP (SCC = 928)
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