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 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.

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1. Introduction

Productivity growth – improvement in the rate at which the economy transforms inputs into aggregate output– is the main driver of long-run increases in living standards for advanced economies (Jones 2016). However, what if today's production has significant implications for future output? Increasingly, it is understood that the rising concentration of carbon dioxide in the atmosphere, which has been a byproduct of production since the Industrial Revolution, negatively impacts both the climate and the economy (e.g. Nordhaus 1977, Nordhaus and Boyer 2003, Hassler et al. 2016, Nath et al. 2024, 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 consume in the future, rather than today.

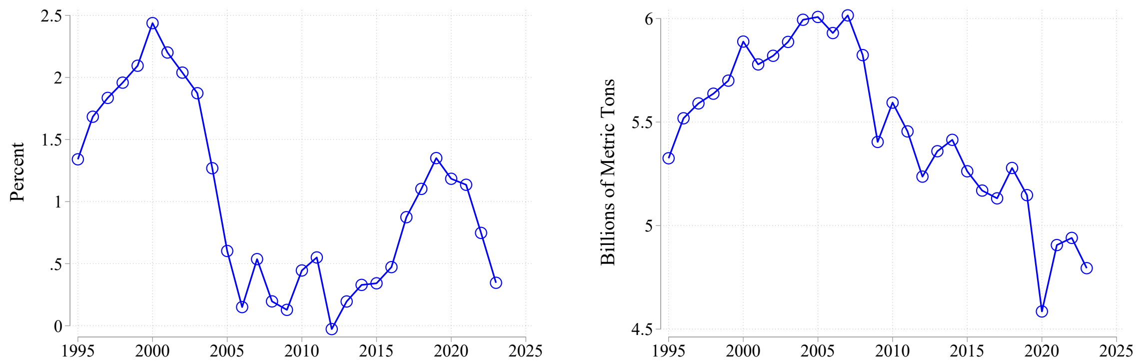
Economists have long acknowledged that measures of economic activity are only welfare-relevant if they accounts for all changes to future consumption that arise as a result of today's production (e.g. Weitzman 1976). Yet standard productivity statistics do not adjust for the effect of emissions on future consumption. This omission is particularly relevant in light of the fact that recent productivity growth has been sluggish in most advanced economies (Fernald et al. 2025). In the United States, for example, annual productivity growth was only 0.6% over the past two decades (Figure 1a). That decline was joined, however, by a significant decline in carbon emissions (Figure 1b). To quantify the extent to which lower carbon emissions mitigate the slowdown of growth, we need a productivity measure that integrates both traditional productivity and the benefits of reduced emissions.

This paper proposes a measure of productivity that is adjusted for carbon emissions. 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 consumption, taking the damage of today's emissions on future consumption into account. We derive TFPE as the welfare-relevant measure of productivity in a general framework nesting canonical models that combine macroeconomic analysis with analysis of climate damages, in particular integrated assessment models (see, e.g., Nordhaus 1977, Muller et al. 2011, Golosov et al. 2014, Hassler and Krusell 2018), and derive the expression for TFPE using standard assumptions on production, emissions, and discounting.

It may seem unconventional to define productivity as a forward looking variable, that takes into account the effect of today's emissions on future consumption. We explain, however, that this is also a feature of standard total factor productivity (TFP) measures such as the Solow residual. That is because today's output is used both for consumption and investment. Weitzman (1976) shows that when investment goods are competitively priced, net investment encodes the present value of future consumption that results from it. Just like TFPE, productivity statistics that measure the rate at which input generate net output are thus also forward looking, in the sense that they capture the effect of today's inputs on future consumption.[1]

[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 result are provided in Weitzman and Löfgren (1997) and Weitzman (1998).

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 (2014a). The right-hand figure plots carbon dioxide emissions in billions of metric tons.

We find that TFPE is straightforward to calculate. It requires data on traditionally-measured TFP, carbon dioxide emissions, and aggregate output, all of which are publicly available across countries and over long periods of time. In addition, calculating TFPE requires an estimate of the marginal effect of a unit of emissions on the present value of consumption – also known as the social cost of carbon. This is a frequently estimated object in the literature as it determines the optimal Pigouvian carbon tax (Hassler and Krusell 2018). In the calculations that follow, the social cost of carbon therefore acts as a sufficient statistic, embodying any assumptions or forecasts on the damage that emissions impose on output directly, through changes in production factors, or both; how long these damages last; and how future consumption is discounted. Assumptions on the cost of carbon also embed the degree to which to which society internalizes global damages from its emissions.

The true level of the social cost of carbon is by no means settled in the literature. We therefore 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 metric ton of carbon dioxide. We show that even the top end of these estimates imply that emissions-adjustment to the level of productivity is small (in the region of 1.5-10%), and the difference in the growth rate of TFPE and TFP under those estimates is therefore minimal. That is particularly true for estimates that disregard global externalities – as advocated, for example, during the 2017–2021 U.S. administration. When these low estimates of the cost of carbon are correct, the macroeconomic implications of climate change are therefore dwarfed by even the smallest productivity gains.

Recent estimates of the social cost of carbon suggest, however, that damages might be much larger. In particular, 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. That is why, rather than choosing particular value of the social cost of carbon, we quantify TFPE for two values: the cost of carbon estimated by Bilal and Känzig (2024), as an upper bound, and a more nuanced estimate of \$252 for the cost of carbon from a meta analysis by Moore et al. (2024). Both of these estimates assume that countries internalize the global damage from emissions. While our framework can equally be used to measure TFPE for domestic damages, we quantify TFPE using cost of carbon estimates based on global damages as this is the usual approach in policy evaluations (Stern et al. 2022, National Academies of Sciences, Engineering, and Medicine 2017).

The social cost of carbon estimated by Bilal and Känzig (2024) far exceeds the typical estimate in the literature and the resultant productivity series, and estimates using this social cost of carbon are likely an upper bound of how different the path of TFPE and TFP might be. At the same time, even these high estimates only consider the economic cost of climate change. They do not consider (e.g.) broader human costs, which may be of the same order of magnitude (Carleton et al. 2022). Adjusting productivity for such non-consumption utility costs of climate change yields an identical expression for TFPE, as this amounts to an alternative definition of the social cost of carbon. In addition, even Bilal and Känzig's estimates for the social cost of carbon assume that the costs of climate change are linear in temperature changes, which means that these estimates will underestimate the cost of climate damage if true costs are convex.

We find that trends in TFPE growth differ markedly from trends in traditionally measured productivity growth for high estimates of the social cost of carbon. For the United States, for example, we find that the reduction carbon emissions in Figure 1b reduces the slowdown of productivity growth by 0.4 percentage points. In contrast, TFPE growth in the 1990s is lower than 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. The slowdown is not reversed for low estimates of the cost of carbon, but we still find a less pronounced slowdown for those estimates.

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 average productivity growth between 2010 and 2020 negative.

We also quantify the 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, the benefit of 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.

Related Literature. We build on an extensive literature that studies the interaction of climate and the macroeconomy. Within that literature, our paper is closest to work on "green" national accounts. It builds on the insight of Weitzman (1976) that net national product – aggregate output net of capital depreciation – measures the present value of consumption that households will derive from today's output in the future. 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 that they will deliver. This logic extends to carbon emissions, in the sense that they deplete the stock of "environmental capital", thus lowering future consumption. 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 output "green GDP". This point has been explored in an extensive literature with seminal references including Solow (1986), Hartwick (1990) and Weitzman and Löfgren (1997). Dasgupta (2009) provides a full review.

One could obtain an emissions-adjusted productivity series by calculating a usual productivity index (e.g. the Solow residual) for green GDP. Our approach is conceptually different, though tightly related. We derive TFPE from an integrated assessment model in the spirit of Nordhaus (1992). Carbon emissions in such models reduce output both directly through a damage function (i.e. a reduction in environmental capital – as in green national accounts), but also through an additional indirect channel, which captures that higher emissions can reduce output by lowering the accumulation of other production factors. The indirect channel appears to explain a large share of the persistent effect of temperature changes on output in the data (Bilal and Känzig 2024). If green GDP is calculated by subtracting both the direct and the indirect costs of carbon emissions, however, either approach to modeling the macro effects of climate change yields the same expression for TFPE.

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 estimated Environment-Adjusted Total Factor Productivity for 1996-2018 (Rodríguez et al. 2018).[2] While we share the high-level motivation of constructing economic aggregates that account for environmental damage, the approach is different.[3] 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, TFPE is dynamic: it captures the economy's ability to convert 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 the social cost of carbon. Finally, a potential drawback of these calculations is that marginal elasticities are used to estimate the ef-

[2] 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.

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

fects of potentially infra-marginal changes in emissions. Our methodology uses insights from the green accounting theory to bypass this difficulty.[4]

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.[5] We also relate to the literature that emphasizes interactions between climate change and endogenous growth (Acemoglu et al. 2012, Acemoglu et al. 2016).[6] 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.[7] 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 both consumption per capita and population growth into account. 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.

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.

[4] 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.

[5] 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.

[6] 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.

[7] The use of TFPE also assures that the welfare benefits of rising use of renewables (e.g., Arkolakis and Walsh 2023) are captured by productivity statistics.

2. Framework

This section introduces the framework in which we derive emissions-adjusted total factor productivity (TFPE). We describe the environment in Section 2.1 and Section 2.2, and derive TFPE in Section 2.3. Section 2.4 presents theoretical extensions while Section 2.5 discusses TFPE measurement at the country level.

2.1. Technology

Consider the following closed economy. The production side of the economy is consistent with canonical models in the macro-climate literature.[8] The economy's output Y_t at time t is given by

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

which obeys the functional form proposed by Nordhaus (1992). In the expression, $A_t F_t(\mathbb{K}_t)$ 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 $\mathbb{K}_t$. Those factors can include various types of labor as well as human capital.[9] The damage function $D_t(\cdot)$ records the damage caused by the stock of carbon, S_t. This stock is determined by the full history of emissions between the pre-industrial era and time t, that is $S_t = L(E^t)$, where $E^t \equiv \{E_0, E_1, ..E_t\}$ as in Golosov et al. (2014).

Two observations with regards to the vector $\mathbb{K}_t$ are in order. First, note that in principle one could subsume the stock of emissions S_t into $\mathbb{K}_t$. However, keeping these terms separate is useful not only because it aligns the setup with the macro-climate literature, but also because our focus is precisely the measurement of productivity adjusted for carbon emissions. Second, while not necessary for any of the results, it is useful to think of the factors $\mathbb{K}_t$ as observed by the national statistician and priced appropriately by the market. This focuses our analysis on the role of carbon emissions as opposed to other production factors that might not be properly measured or priced.[10]

Turning to the flow of emissions, we assume that carbon dioxide emissions are a byproduct of production that are not recorded in standard aggregates in the national accounts.[11] The relationship between production and emissions nests the specification in Nordhaus (1992) and is 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 carbon that an input bundle emits.

[8] We extend the framework for country-level productivity measurement in an open-economy setting in Section 2.5.

[9] Practitioners in productivity measurement typically differentiate labor by observable characteristics such as gender, age, and education level. Fernald (2014a) provides a brief discussion.

[10] Of course there may be other inputs into production that are not properly measured or priced. Our framework can be readily applied to adjust productivity for any of such factors. We elaborate on this point in Section 2.4.

[11] Emissions are also not recorded as part of the national accounts 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.

Note that we impose no functional form on 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. This means that the framework nests macro-climate models with explicit assumptions on either of these equations.

2.2. Preferences and demand

Turning to the demand side of the economy, we define aggregate output as measured in the national accounts, and specify a welfare function. The former is useful to show that our expression for emissions-adjusted total factor productivity is tightly related to how productivity is typically measured, while we use the latter to show that our productivity measurement is welfare-relevant.

The national statistician records aggregate output by summing consumption and investment:

$$Y_t = C_t + \mathrm{p}_t \mathbb{I}_t.$$

The vector of investment $\mathbb{I}_t$ gives the change in each of the capital inputs over time before depreciaton. Inputs that do not accumulate through investments, such as labor, have zero investment in $\mathbb{I}_t$. Consumption is the sum of household and government consumption and serves as the numeraire. The vector of investment good relative prices is p_t. In what follows, we assume that investment goods are priced competitively, in the sense that each element in p_t corresponds to the marginal rate of transformation of investment goods to consumer goods, so that resources are efficiently allocated across investment goods and consumption. As we explain later, this assumption implies that standard measures of productivity growth are welfare-relevant in the absence of climate damages.[12]

Turning to preferences, we assume that both current and future consumption matter for welfare. This is essential, as forward-looking preferences imply that future climate damages are costly. In the baseline, we assume that preferences are indexed by the present value of consumption, along

$$\boldsymbol{V}_t = \mathbb{E}_t \left[\sum_{s=0}^{\infty} \prod_{k=t}^{t+s} \beta_k C_{t+s} \right], \tag{3}$$

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. We merely impose this here for expositional clarity.[13]

2.3. Productivity

We define emissions-adjusted total factor productivity, TFPE, as the marginal effect of a bundle of inputs $F_t(\mathbb{K}_t)$ on the present value of consumption. We explain below that this is a useful definition of productivity in a dynamic economy (where today's output affects future economic activity), and one that coincides with standard productivity measures in the absence of emissions.

[12] Wedges that don't affect the relative investment price, e.g. homogeneous markups, don't invalidate the assumption.

[13] In Section 2.4 we detail the calculation for $TFPE_t \equiv \mathrm{d}\,\boldsymbol{U}_t / \mathrm{d}\,F_t(\mathbb{K})$ where $\boldsymbol{U}_t$ is defined as the present value of utility.

In a static economy, where all output is consumed, productivity is the rate at which bundles of inputs can be converted into consumption. In contrast, inputs in a dynamic economy affect consumption in the future, as inputs are also used to produce investment goods. A productivity measure that quantifies an economy's ability to convert inputs into welfare must take these dynamic effects into account. In Proposition 1 below, we show that standard total factor productivity measures (TFP) indeed capture the effect of inputs on the present value of consumption, in the absence of climate damages. That result naturally follows from the envelope theorem: if investment goods are competitively priced, their price encodes the present value of consumption that these investments deliver in the future. This intuition extends beyond the first order that we will rely on: Weitzman (1976) derives that when national output is measured net of depreciation, it yields the present value of future consumption that will be derived from it. A productivity measure that quantifies the effect of inputs on aggregate output therefore also quantifies their effect on the present value of consumption.

TFPE accounts for the facts that, in a framework such as ours, the use of inputs in production also comes with emissions. These damage future output and thus reduce future consumption. They do so both by directly lowering the value of $D(\cdot)$, thereby effectively acting as a negative investment in unmeasured environmental capital, and by reducing future input accumulation. This means that standard productivity statistics that quantify the rate at which inputs are transformed into output will overstate the economy's efficiency. Proposition 1 derives the expression for TFPE formally:

Proposition 1. *The present value of the marginal effect of a bundle of inputs $F_t(\mathbb{K}_t)$ on the present value of consumption $\boldsymbol{V}_t$, TFPE, is given by*

$$TFPE_t = TFP_t \left(1 - \frac{E_t}{Y_t} SCC_t\right) \tag{4}$$

where TFP_t is total factor productivity, defined as the marginal effect of a bundle of inputs on output:

$$TFP_t \equiv \frac{\partial Y_t}{\partial F_t(\mathbb{K}_t)} = A_t D(S_t), \tag{5}$$

and where SCC_t is the social cost of carbon, measured in the same units as output Y_t, defined as the present value of the consumption reduction induced by a marginal unit of emissions:

$$SCC_t = -\mathbb{E}_t \left[\sum_{s=1}^{\infty} \prod_{k=t}^{t+s} \beta_k \frac{\mathrm{d}\, C_{t+s}}{\mathrm{d}\, E_t} \right].$$

Derivation: Define $TFPE_t$ as the marginal effect of a bundle of inputs on the present value of consumption. The marginal effect can be decomposed into three parts:

$$TFPE_t \equiv \frac{\mathrm{d}\, \boldsymbol{V}_t}{\mathrm{d}\, F_t(\mathbb{K}_t)} = \frac{\partial \boldsymbol{V}_t}{\partial C_t} \frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \boldsymbol{V}_t}{\partial \mathrm{p}_t \mathbb{I}_t} \frac{\partial \mathrm{p}_t \mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \boldsymbol{V}_t}{\partial E_t} \frac{\partial E_t}{\partial F_t(\mathbb{K}_t)}.$$

The first term is the change in the present value of consumption due to higher consumption today, the second term is the change from investments, and the final term is the change from emissions.

It is straightforward to simplify this expression. The partial derivatives with respect to today's consumption and today's investments both equal 1. For contemporaneous consumption this is trivial (see equation 3). For investments, the unit derivative follows from the fact that the competitive investment goods p_t encodes the present value of consumption by the envelope theorem. Thus, for the present value of consumption, it does not matter on the margin whether inputs are used to produce investment or consumption goods. The total derivative can therefore be written as:

$$\begin{aligned} TFPE_t &= \frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \mathrm{p}_t \mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \boldsymbol{V}_t}{\partial E_t}\frac{\partial E_t}{\partial F_t(\mathbb{K}_t)}, \\ &= TFP_t + \frac{\partial \boldsymbol{V}_t}{\partial E_t}\frac{\partial E_t}{\partial F_t(\mathbb{K}_t)} \end{aligned} \tag{6}$$

where TFP_t is traditionally-measured productivity as defined in Proposition 1.[14] It follows that in an economy without emissions or where consumption is immune to emissions, TFP_t is welfare-relevant:

Corollary 1. *In the absence of climate damages, TFP_t measures the marginal effect of a bundle of inputs on the present value of consumption.*

If climate damages do exist, however, there is an additional term in the TFPE calculation. It may seem that this term can only be calculated with knowledge of the damage function and the production function, on which we made few assumptions. We next show, however, that this adjustment term can be written as a simple function of emissions, aggregate output, and the present value of the marginal damage to future consumption that is induced by an additional unit of emissions. The latter is known as the Social Cost of Carbon (SCC) in the macro-climate literature (see, e.g., Hassler et al. 2016). Although the cost of carbon is not observable, it is widely estimated in the literature, as it determines optimal Pigouvian carbon taxes. It takes two steps to derive this. First, use the emissions equation (2) in place of the derivative of emissions with respect to inputs:

$$\frac{\partial E_t}{\partial F_t(\mathbb{K}_t)} = \phi_t = \frac{E_t}{Y_t} A_t D_t(S_t)$$

We then use the fact that $\partial \boldsymbol{V}_t / \partial E_t$ is the textbook definition of the SCC. Formally, we can write:

$$\frac{\partial \boldsymbol{V}_t}{\partial E_t} = \mathbb{E}_t \left[\sum_{s=1}^{\infty} \prod_{k=t}^{t+s} \beta_k \frac{\mathrm{d}\, C_{t+s}}{\mathrm{d}\, E_t} \right] \equiv -SCC_t.$$

Inserting the definition of the SCC into (6), and using $TFP_t \equiv A_t D_t(S_t)$, we obtain the top equation in Proposition 1. ■

[14] Note that we could equally define TFP_t as the ratio of Y_t and $F(\mathbb{K}_t)$, given the functional form of the production function (1). This functional form matches the multiplicative structure that other work on productivity measurement assumes including (e.g.) Fernald (2014b). The advantage of defining $TFPE_t$ as the *marginal* effect of inputs on the present value of output is that the resultant expression requires an estimate of the marginal damage from emissions. That is useful, because that marginal damage is known as the social cost of carbon, and is frequently estimated in prior work.

By calculating TFPE along (4), the estimates inherit assumptions on the discount rate and the degree to which global damages are internalized from the estimate of the social cost of carbon. Those estimates serve as a "sufficient statistic" to express the costs of emissions intensity of production. 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.

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 extension derives TFPE if welfare is concave in consumption, by introducing a utility function. Third, we explain that it is straightforward to extend our measurement framework to variables other than carbon that affect future output, such as human capital accumulation and 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 other utility costs of climate change into account. It is straightforward to show that the expression for TFPE in Proposition 1 can be applied to broader costs of climate change, as such costs simply imply a different definition of the social cost of carbon. Say climate damages impose a non-consumption cost on welfare $\Omega(S_t)$, so that welfare out of consumption net of the damages equals

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

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 $TFPE_t$ is largely unchanged from Proposition 1:

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

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

$$\boldsymbol{U}_t = \mathbb{E}_t\left[\sum_{s=0}^{\infty}\beta^s u\left(C_{t+s}\right)\right] \quad , \quad TFPE_t \equiv \frac{\mathrm{d}\,\boldsymbol{U}_t}{\mathrm{d}\,F_t(\mathbb{K}_t)}\frac{1}{u'(C_t)}, \tag{7}$$

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 (6) 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:

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

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 (6) 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 present value of investments reflect the stochastically discounted present value of their effect on investments, 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

$$\begin{aligned}\frac{\mathrm{d}\,\boldsymbol{V}_t}{\mathrm{d}\,F_t(\mathbb{K}_t)} &= \frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \mathrm{p}_t \mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \sum_{X^j\in X}\left(\frac{\partial \boldsymbol{V}_t}{\partial X_t^j}\frac{\partial X_t^j}{\partial F_t(\mathbb{K}_t)}\right),\\ &= TFP_t\left(1 - \sum_{X^j\in X} - \frac{\partial X_t^j}{\partial Y_t}\frac{\partial \boldsymbol{V}_t}{\partial X_t^j}\right).\end{aligned} \tag{8}$$

Thus, if the relationship between X_t^j and both aggregate output and the present value of consumption is known, one 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 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 (8) 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 (4) 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 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 a competitive equilibrium with no externalities.[15] The green accounting liturature 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 Appendix A we show that the productivity index for green GDP is identical to the expression for TFPE that we derive in equation (4), as long as the same social cost of carbon is assumed when subtracting the costs of emissions from aggregate output. It is straightforward to understand why the productivity index for green GDP and 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.

2.5. TFPE at the country level

We have thus far derived TFPE for a closed economy who's stock of carbon is determined by its own history of emissions. In practice, the stock of carbon is determined by global emissions. Hence foreign emissions affect domestic consumption, and domestic emissions affect foreign consumption.

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

When calculating TFPE at the country level, these global spillovers affect the calculation through the social cost of carbon. A key consideration is whether preferences only include the domestic damage caused by emissions, or whether a country internalizes the global effects of its emissions. In the quantitative sections of the paper, we use estimates of the cost of carbon that assume full internalization of global damages, as this is the approach that is most frequently used in policy evaluations (Stern et al. 2022, National Academies of Sciences, Engineering, and Medicine 2017). In that case, the expression for TFPE in country i at time t is largely unchanged:

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

It is equally possible, however, to use estimates of the cost of carbon that focus solely on domestic economic costs, sometimes referred to as the domestic cost of carbon (DCC):

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

This was the approach used to evaluate climate policy in the United States between 2017 and 2021 (Voosen 2021). In the quantification exercise we do not calculate TFPE using the DCC. That is because the cost of emissions under the DCC is so small compared to aggregate output Y_{it} in most countries that the adjustment to productivity is minimal. While that makes it unnecessary to calculate TFPE for the DCC, we do not want to discard this as a null result – rather, we posit that when evaluating the costs and benefits of climate policy on the basis of domestic costs of emissions, the smallest improvements to productivity would dominate the benefits of efforts to reduce emissions.[16]

A practical concern when measuring TFPE at the country level is that advanced economies have moved some of their emissions to other countries. These imported emissions may cause an overestimation of TFPE growth for advanced economies, and an underestimation of TFPE growth in developing countries. In the quantification we address this by using trade-adjusted emissions, also known as consumption-based emissions. In contrast to territorial emissions, these series attribute carbon emissions to the country where goods are consumed rather than where they are produced. In Appendix B we provide a brief formal motivation for using trade-adjusted emissions series when calculating emissions-adjusted total factor productivity, although in practice the series are highly correlated.[17] In addition to the theoretical motivation in the appendix, using trade-adjusted 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.

[16]For economies in colder locations (such as Canada and the United Kingdom), the DCC can even be negative (Nath et al. 2024). If the DCC is used to guide climate policy in these countries, they should endeavor to maximize emissions.

[17]For example, the correlation between growth of trade-adjusted and territorial emissions in the United States is 0.93.

3. Quantification

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 summarize our data sources in Section 3.1. The social cost of carbon has been extensively estimated in the literature, and in Section 3.2 we justify the two values that we use.

3.1. Observable variables

Data on traditionally measured productivity growth and gross domestic product comes from the Penn World Table (edition 10.01, see Feenstra et al. 2015).[18] We also use 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 for a large set of countries. Figure A1 in Appendix C plots emissions for selected countries.

3.2. Social cost of carbon

Besides these observables, we need an estimate of the cost of carbon. 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.

As explained in Section 2, we focus on SCC estimates that internalize the global externality of carbon emissions. Our first series for TFPE are based on estimates of the SCC of Bilal and Känzig (2024). Their estimates suggest the SCC in 2017 of $923 (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. Dell et al. (2014) provide an detailed survey of this approach. 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 correlation 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

[18] 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 2014a, 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.

general equilibrium model based on Nordhaus (1992), with a discount rate of 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 SCC 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 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 as proposed in Section 2.4.1, e.g., those related to the loss of health, heightened uncertainty due to weather extremes, loss of biodiversity, animal welfare considerations, would further raise the estimate of damages.

To compute TFPE over time 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 growth rate implied by a sample of key studies of the social cost of carbon. 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 compute 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 across these models is 2.1%, and the corresponding mean is 2.6%.[19] In light of this, we assume a growth rate of the SCC of 2.1% per year in subsequent calculations.

[19]We find close to no correlation between the level of the SCC and its growth rate across models. Note that the rising SCC implies that, for constant TFP and E/Y, TFPE falls over time. That is accurate, because constant emissions intensity and rising costs of emissions imply that the economy's ability to convert inputs into consumption is declining over time.

Figure 2. 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 (4). The TFP series comes from the latest edition of the Penn World Table.

4. Results

This section presents the 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 trade-adjusted emissions for a wide range of countries.

4.1. Trends in TFPE Growth

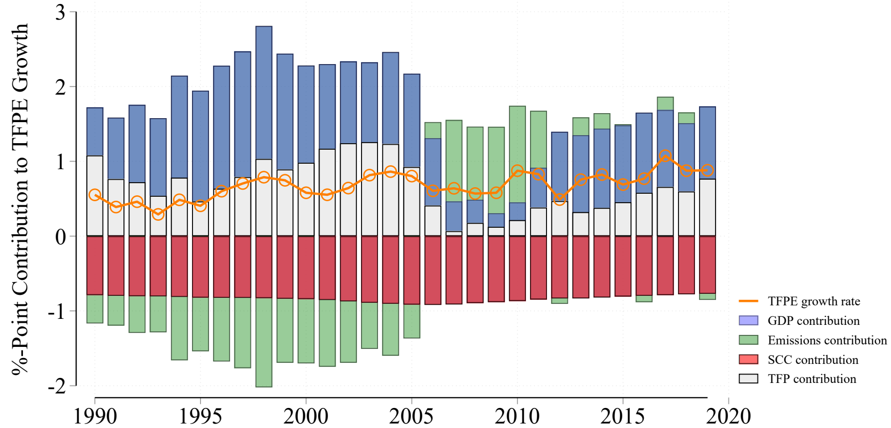
Our headline results for the United States are shown in Figure 2, which plots the trajectory of U.S. TFP and TFPE growth. Traditionally measured TFP growth exhibits a familiar pattern: it is high in the 1990s through 2005, a boom that is widely ascribed in the literature to the rise of information and 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).

The figure yields two main results. The first 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 carbon that reflects the recent consensus, global economic costs of emissions would be overwhelmed by even minor improvements in productivity.[20]

The second result is that the path of productivity changes significantly for a social of carbon of $928. 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,

[20] 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 3. Drivers of TFPE Growth for the United States (SCC = \$928)



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 (orange-circled line).

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 traditional TFP disappears.

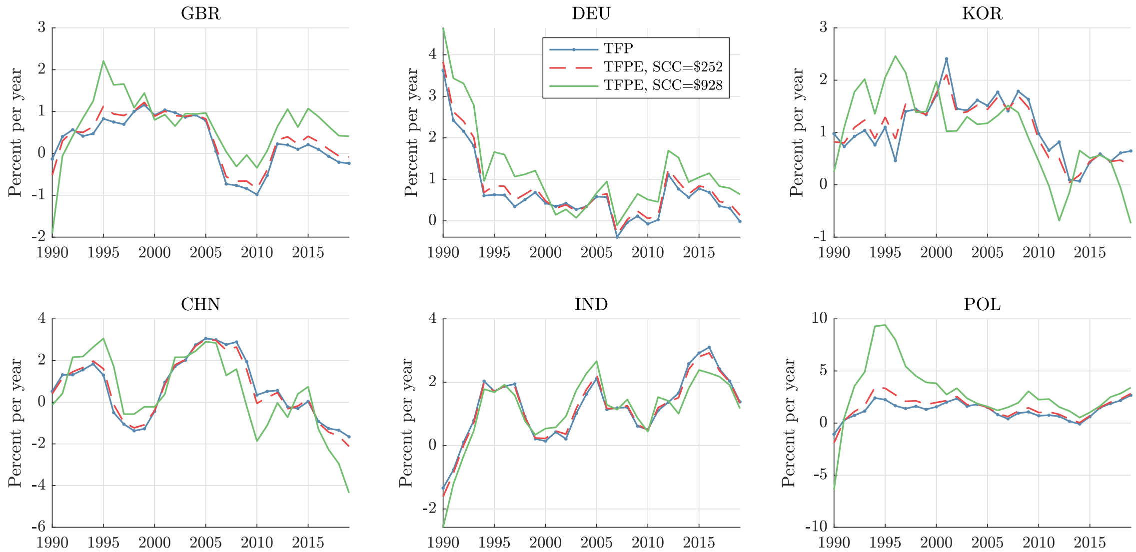
What drives the stable growth of emissions-adjusted productivity under the high social cost of carbon? Figure 3 decomposes total growth into the contribution of traditional productivity growth, growth in emissions and output, and growth in the social cost of carbon, along

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

The terms in this decomposition are discrete-time approximations of the partial derivative of TFPE with respect to the term's variable, multiplied by the change in that variable.

The figure shows that the stable TFPE growth is driven by the fact that, weighted by the social cost of carbon, emissions-intensity of production was rising in the 1990s and the early 2000s, but falling after 2005. Narrowing in on individual contributors, 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. 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.

Figure 4. TFP and TFPE Growth in Selected Economies



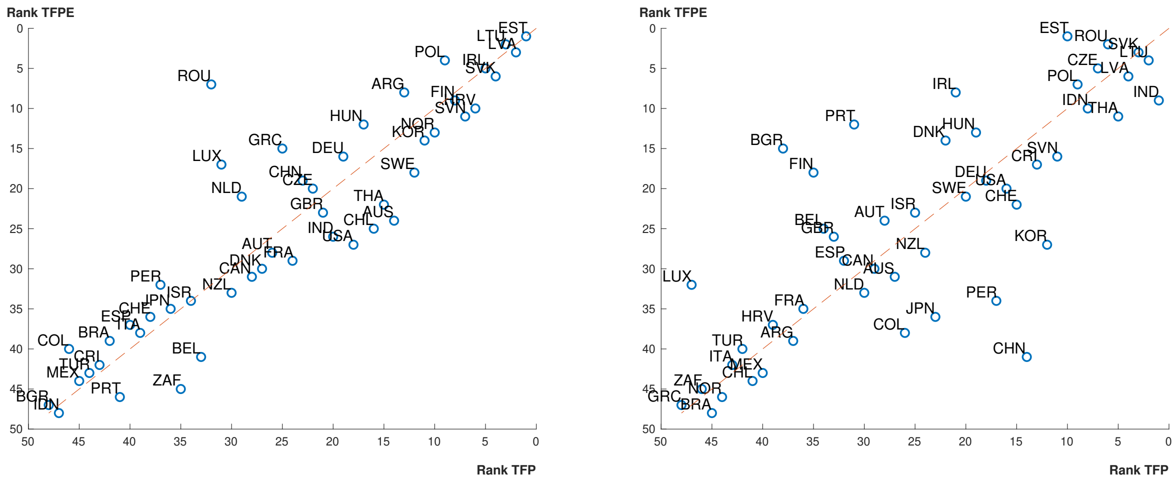
Notes: Each panel shows average annual growth of TFP (blue bars) and TFPE (at a social cost of carbon of $928, green bars, or $252, stars). From left to right, the panels present data for the United States, United Kingdom, Germany and Japan. TFPE is calculated using equation 4. The TFP series comes from the latest edition of the Penn World Table.

Figure 4 provides counterparts to Figure 2 for a number of additional economies.[21] Note that the vertical axes differ in each sub-figure. The figure shows that trends in TFPE differ strongly around the world. 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. 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 TFPE growth in subsequent years.

The advanced economies in Figure 4 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 in Figure 2 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 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

[21] We decompose developments in TFPE growth into various contributors for these countries in Section 4.2.

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 (4). Traditionally measured TFP growth is obtained from the Penn World Table. The dashed-red reference line is 45 degrees.

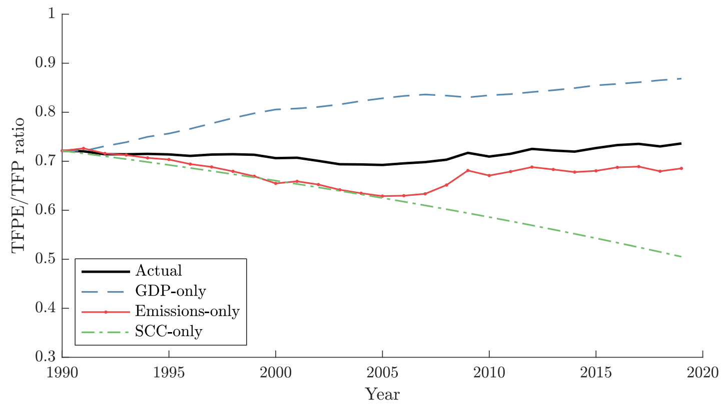
top-left quadrant of the figure. Among these are Belgium, Denmark, Israel, New Zealand, Canada, and Italy. While this reversal pattern is not universal, the figure also documents that for the majority of the developed economies, TFPE growth has slowed much less than TFP growth. Of the countries shown,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

Expanding the analysis of TFPE to many countries, Figure 5 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 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.

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, 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, 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. TFP and TFPE in Levels for the United States



Notes: The black line in the right-hand figure plots counterfactual paths for the ratio of TFPE and TFP, that is $\frac{TFPE_t}{TFP_t} = 1 - \frac{E_t}{Y_t} SCC_t$ (see equation (4)) for the high SCC. The right-hand figure also plots 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 Penn World Table.

4.2. The gap between TFP and TFPE in levels

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 6 and 7 address this by plotting the ratio of TFP and TFPE for the United States and the selected economies.

The solid-black line in the figures plots the ratio of TFPE and TFP assuming the high SCC. The ratio equals one for an economy without emissions and zero for an economy where emissions cause damages equal to today's GDP.[22] The ratio has a natural interpretation: it equals the productivity-equivalent gains of achieving net-zero carbon emissions.[23] 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.

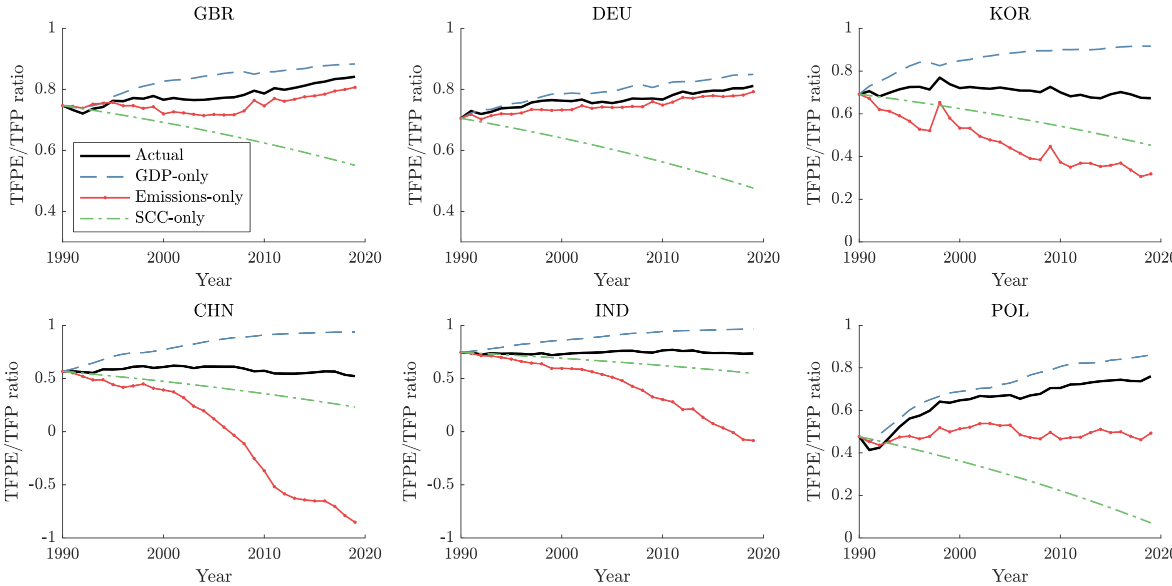
For the United States, the TFPE over TFP ratio varies between 0.7 and 0.75, which means that the U.S. economy was 25% to 30% less productive once the present value of climate damages are taken into account. The 2019 ratio is higher for the United Kingdom, Germany and Korea, but substantially lower for China and Poland. Between 1990 and 2019, the gap remains reasonably constant in the United States. That is because, despite the fact that the growth of both productivity statistics differs significantly in particular years, their average growth is similar over the full sample.

The figures confirm 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 the current climate damage an economy is imposing, and space for further TFPE growth in coun-

[22] 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.

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

Figure 7. The Wedge between TFPE and TFP and Counterfactuals in Selected Economies



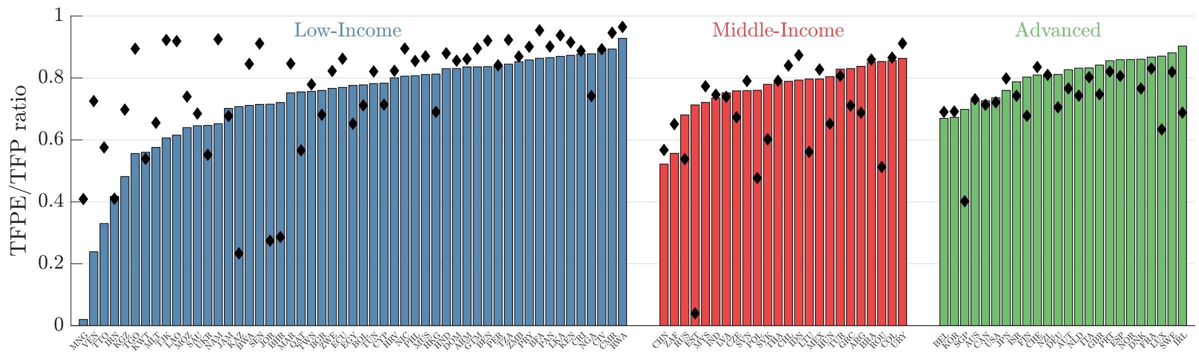
Notes: The black line in the right-hand figure plots counterfactual paths for the ratio of TFPE and TFP, that is $\frac{TFPE_t}{TFP_t} = 1 - \frac{E_t}{Y_t} SCC_t$ (see equation (4)) for the high SCC. The right-hand figure also plots counterfactual paths for this ratio if only one of the components was 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.

tries with low initial TFPE over TFP ratios is naturally greater than in a country where emissions are already low.

The other lines provide counterfactuals for alternative paths of the variables that jointly drive the ratio of TFPE over TFP. Red-circled 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-dashed and green dash-dotted 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.

In line with the decomposition in Figure 2, 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), 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 growth measured with the 1990 SCC exceeded that of GDP in 1990 by nearly twofold.

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 Table or from the OECD.

4.3. TFPE along the development path

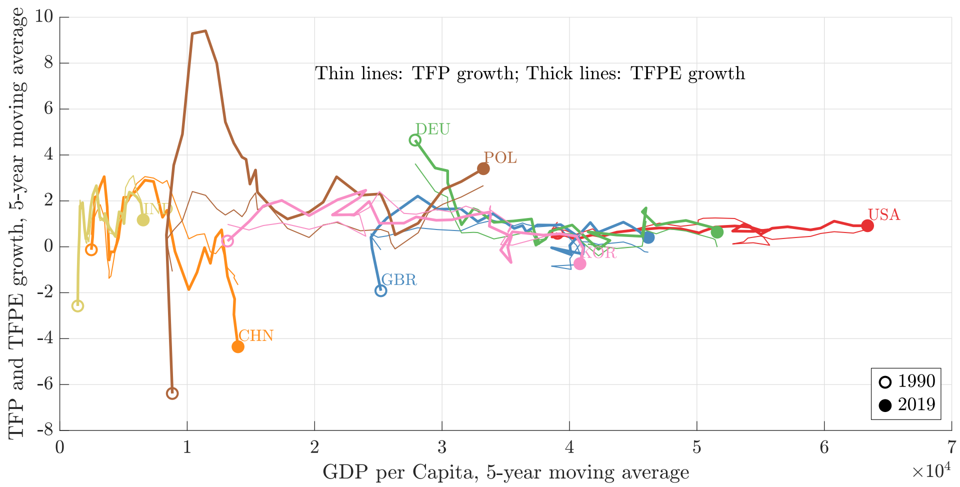
As a final empirical exercise, we examine how TFPE evolves along the development path. In contrast to the well-known stylized fact that productivity levels are higher in developed economies, we find no clear relationship between TFPE over TFP (or TFPE growth) and the level of development. To show this,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

Results are provided in Figure 8. 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 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 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, many of the poor nations recorded significant declines in TFPE-TFP ratio, while most advanced economies recorded improvement.

Figure 9. 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 Table.

Narrowing in on the third result, we find that the positive relationship between TFPE growth and development status is not a historical regularity. One way to show that is to plot the path of a country's TFPE growth against its historical per-capita income. If there is indeed a time-invariant relationship between economic development and TFPE growth, we should see that these are positively related. We do so in Figure 9, which 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.[24] 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, as well as 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 economy in the 1990s led to a decent pace of TFP growth but an exceptionally high rate of TFPE

[24] The convergence gradient 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.

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 measure of productivity, TFPE, that adjusts for the climate damage induced by carbon dioxide emissions. TFPE measures the economy's ability to transform bundles of inputs into units of present-value consumption, 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 growth in 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: 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.

The framework we propose opens several avenues for future research. Our estimates are consistent with the broader climate economics literature on the economic damages of carbon emissions, and other greenhouse gases can be readily incorporated into the analysis. Yet it is increasingly recognized that climate change has far-reaching consequences beyond the production boundary. The framework can be naturally extended to capture the adverse effects of emissions that go beyond their direct impact on climate. Future work could build on this methodology to broaden the concept of damages, encompassing environmental, biological, and other wide-ranging costs of climate change. It can also be used to adjust productivity growth for variables unrelated to climate that baffect 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 —- 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 competitive equilibrium 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 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 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 $D' \oint 0$. 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 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:

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

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. Territorial versus consumption-based emissions

We rely on consumption-based emissions series to calculate TFPE. Consumption-based emissions, also known as trade-adjusted emissions, 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 have higher territorial emissions than consumption-based emissions.

In practice, consumption-based emissions and territorial emissions are highly correlated in most countries. For the United States, the correlation between the growth rate of consumption-based and territorial emissions is 0.93. Figure A1 illustrates this more broadly by plotting the path of both series for selected economies. Thus, the path of TFPE is similar regardless of the series used.

The use of consumption-based emissions is motivated by a simple extension of the framework. Rather than the closed economy's emissions function (2), assume that emissions E_{it} in any country i are driven by a combination of domestic production and by production in every other country in the world. Akin to the functional form in (2), 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

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

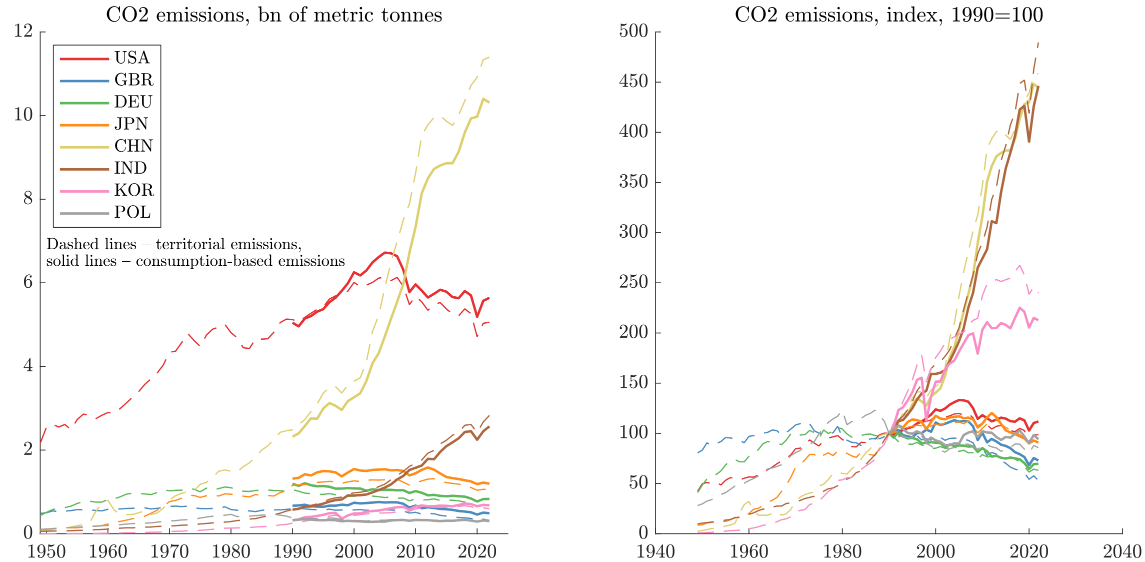
where E_t denotes global emissions, $E_t = \sum_{j \in J} E_{jt}$. Rewriting yields the familiar TFPE expression:

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

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.

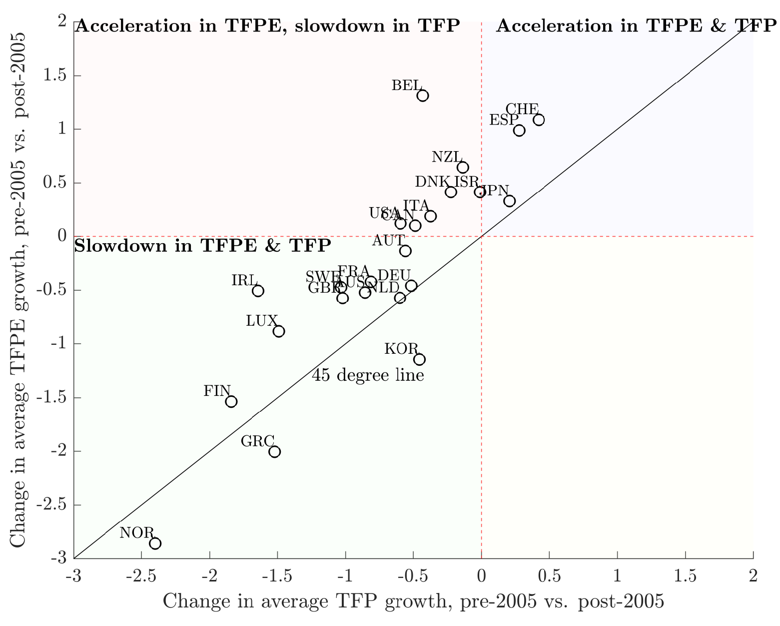
Appendix C. Additional Tables and Figures

Figure A1. Carbon Dioxide Emissions in Selected Economies



Notes: This figure plots the path of annual territorial and consumption-based CO_2 emissions from Our World in Data (Ritchie et al. 2023). 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.

Figure A2. 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 Table.

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		\$252	\$928		\$252	\$928	\$252	\$928	\$252	\$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	TFPE	TFP	TFPE	TFPE	TFPE vs. TFP		TFPE vs. TFP	
SCC		$252	$928		$252	$928	$252	$928	$252	$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