NBER WORKING PAPER SERIES

THE GROWTH OF NATIONS REVISITED:
GLOBAL ENVIRONMENTAL ACCOUNTING FROM 1998 TO 2018.

Aniruddh Mohan
Nicholas Z. Muller
Akshay Thyagarajan
Randall V. Martin
Melanie S. Hammer
Aaron van Donkelaar

Working Paper 27398
<http://www.nber.org/papers/w27398>

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
June 2020

The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

At least one co-author has disclosed a financial relationship of potential relevance for this research. Further information is available online at <http://www.nber.org/papers/w27398.ack>

NBER working papers are circulated for discussion and comment purposes. They have not been peer-reviewed or been subject to the review by the NBER Board of Directors that accompanies official NBER publications.

© 2020 by Aniruddh Mohan, Nicholas Z. Muller, Akshay Thyagarajan, Randall V. Martin, Melanie S. Hammer, and Aaron van Donkelaar. All rights reserved. Short sections of text, not to exceed two paragraphs, may be quoted without explicit permission provided that full credit, including © notice, is given to the source.

The Growth of Nations Revisited: Global Environmental Accounting from 1998 to 2018.
Aniruddh Mohan, Nicholas Z. Muller, Akshay Thyagarajan, Randall V. Martin, Melanie S.
Hammer, and Aaron van Donkelaar
NBER Working Paper No. 27398
June 2020
JEL No. E13,Q51,Q53,Q54,Q56

ABSTRACT

A persistent issue in environmental economics is whether growth is sustainable. Pollution is a key driver of sustainability, which we define as an economy exhibiting falling pollution damages at its balanced growth path. We deduct air pollution and carbon dioxide damages from the national accounts for 163 countries between 1998 and 2018. Global pollution intensity fell from 1998 to 2008, remaining flat thereafter. China highlights the importance of defining sustainability in terms of damages; between 2011 and 2018, physical measures of environmental quality improved, but monetary damage increased by 50 percent. Sustainability based on emissions ignores this rise in damage.

Aniruddh Mohan
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, Penn 15213
aniruddm@andrew.cmu.edu

Randall V. Martin
Washington University - St. Louis
One Brookings Drive, CB 1180
St. Louis, MO 63130
rvmartin@wustl.edu

Nicholas Z. Muller
Department of Engineering, and Public Policy
Tepper School of Business
Carnegie Mellon University
4215 Tepper Quad
5000 Forbes Avenue
Pittsburgh, PA 15213
and NBER
nicholas.muller74@gmail.com

Melanie S. Hammer
Washington University - St. Louis
One Brookings Drive, CB 1180
St. Louis, MO 63130
melanie.hammer@wustl.edu

Akshay Thyagarajan
5000 Forbes Avenue
Pittsburgh, Penn 15213
United States
akshayt@andrew.cmu.edu

Aaron van Donkelaar
Dalhousie University
Halifax, Nova B3H 4R2
Canada
kelaar@Dal.Ca

1 Introduction

A persistent issue in the field of environmental economics is whether observed patterns in growth and development are sustainable. The determinants of an economy's sustainability include population growth, capital intensity and technological progress, and relative rates of savings and consumption. These are also essential elements in neoclassical growth models (Solow, 1956). In fact, the very notion of a steady state income level, foremost in the Solow model, evokes considerations of sustainability. This link became explicit when, writing in the 1970s, after the passage of landmark environmental legislation and during the energy crisis, Solow (1974) proposed that man-made capital should accumulate to offset exhaustible natural resource depletion. Though framed in terms of intergenerational equity, sustainability is at the crux of this and subsequent work (Hartwick, 1977). Also in the 1970s, Nordhaus and Tobin (1973) proposed an augmentation of official output statistics to include (among other omitted services) natural resources and the environment. The motivation was to align the National Income and Product Accounts (NIPAs) with a more inclusive measure of economic welfare. Doing so would alleviate the apparent conflict between growth and degradation of the natural environment. At issue were concerns about sustainability.

These literatures are in agreement about what defines sustainable growth. Solow (1974) points out that balanced growth, in which investment offsets depreciation, can sustain corresponding levels of consumption indefinitely. Equivalently Hamilton (1994, 1996) argued sustainable growth requires non-negative capital accumulation, inclusive of both man-made and natural capital.

This paper infuses the broad based view of capital from the environmental accounting literature into the analysis of steady state income in neoclassical growth models. So equipped, growth models of the sort developed by Solow (1956) are apt tools for assessments of sustainable development.

Although natural capital encompasses a wide and heterogeneous range of resources, we focus on the case of environmental pollution. Our context reflects both data availability and

that pollution is, perhaps, the most crucial determinant of society’s sustainability. In this setting, Brock and Taylor (2010) offer an important advance in the deployment of neoclassical growth models to probe questions of sustainability by including physical emissions in a Green Solow model. Brock and Taylor (2010) concluded that growth is sustainable if emissions fall at the economy’s balanced growth path.

In contrast, this analysis invokes the Solow-Hamilton definition of sustainable growth presented above. The appropriate measure of pollution in this context is monetary damage, as this reflects natural capital depreciation. To this end, the present paper augments Solow’s model to include monetary pollution damage. We argue that growth is sustainable if damage (rather than emissions) falls at the economy’s balanced growth path, as man-made capital accumulation is zero at this point. Rising pollution damage would induce net negative comprehensive wealth accumulation, violating sustainable growth.

We bring the augmented Solow model to a new dataset of integrated economic and environmental accounts for over 160 countries between 1998 and 2018. The augmentation occurs in two areas within the very broad environmental accounting context: monetary damages from fine particulate matter ($PM_{2.5}$) and carbon dioxide (CO_2). To accomplish this, we employ a globally comprehensive database on $PM_{2.5}$ concentrations and CO_2 emissions. Using these data, the empirical analysis estimates monetary damage, or the Gross External Damage (GED), by country-year (Muller, Mendelsohn and Nordhaus, 2011; Muller, 2014, 2020). We then deduct gross damages from gross domestic product (GDP) to estimate environmentally-adjusted value added (EVA). Thus, the paper produces the first set of global, integrated environmental and economic accounts over a 21-year panel. Though our estimates of EVA are not truly comprehensive, prior research shows that these two pollutants cause damages comprising a considerable share of national output in the United States (Muller, 2020; Tschöfen, Azevedo and Muller, 2019).

The augmented Solow model developed in this paper yields an important insight. If marginal damages rise with income, damages peak at a higher level of capital per worker

than do emissions. The key implication of this is potentially divergent conclusions about sustainability. If both emissions and damages peak either before or after an economy reaches its balanced growth path, both yield the same inferences about sustainability. However, if emissions peak before balanced growth and damages after, an economy may be deemed to be growing sustainably, when, from the welfare-based definition proposed above, it is not.

Our empirical results are summarized as follows. Globally, the pollution intensity of output, defined as GED/GDP , fell from 1998 to 2008 and remained flat thereafter. High income countries exhibit declining pollution intensity of output from 1998 to 2018. GED comprised about 10% of GDP in 1998. By 2018, GED fell to under 7% of output. The result of this attenuation of pollution intensity is to increase apparent growth. Though we find a range of growth differentials across high income countries, we present a few notable results here. EVA growth outpaced GDP growth in the United Kingdom (U.K.) by 50-100 basis points on average and in the United States (U.S.) by 30-40 basis points. In the other large economies on the European continent, growth differentials were smaller. In addition, most of the reductions in pollution intensity in the high income countries occurred before the Great Recession.

In marked contrast to the greening of the high income economies, upper middle income countries became more pollution intensive. The GED in this group increased from over 7% of GDP to about 10% in 2018. China drives this result. Despite a five-fold increase in real GDP/capita, its GED began at 11 percent of GDP in 1998 and climbed to 13 percent of GDP in 2018. Due to rising pollution intensity, EVA growth in China was appreciably less rapid than GDP. In the early 2000s, the difference averaged 50 basis points.

In the lower middle income group, pollution intensity grew modestly from 7% to 8% of GDP. Perhaps most notable within this group of countries, India appears poised to follow China's development path as its GED -to-GDP ratio ascended from 8 percent to 10 percent. EVA growth in India lagged GDP by roughly 30-50 basis points after 2005. Finally, the lowest income countries exhibit low levels of pollution intensity (4% of GDP) that was essentially

constant.

Bringing the augmented Solow model to the data, across all countries, damages appear to peak at higher income levels than $\text{PM}_{2.5}$ concentration and CO_2 emissions. This has potentially important implications for inferences about sustainable growth. Perhaps most important from a global perspective are the results for China. Ambient levels of $\text{PM}_{2.5}$ peaked in 2011. Emissions of CO_2 , while increasing, have slowed considerably. Yet, the monetary pollution damages in China, as of 2018, are still rising rapidly. There is no better evidence of the importance of our proposed measure of sustainability, relative to one based on emissions.

While the present paper is the first to develop a global scale set of integrated environmental and economic accounts, the analysis builds on a long literature in environmental accounting. This includes Nordhaus and Tobin (1973), Bartelmus (2009), as well as more recent work focusing on environmental accounting of the U.S. economy (Muller, Mendelsohn and Nordhaus, 2011; Muller, 2014, 2020). The conceptual framework for integration of environmental pollution damage was established by Nordhaus and Kokkelenberg (1999), Abraham and Mackie (2006), and Nordhaus (2006). This analysis also draws on the growth literature, from the early work of Harrod (1939) and Domar (1946) to the neoclassical Solow (1956) model and more recently to Mankiw, Romer and Weil (1992); Mankiw, Phelps and Romer (1995). And as mentioned above, the present paper builds on Brock and Taylor (2010). An additional set of papers, of which Brock and Taylor (2010) is an example, focusing on the Environmental Kuznets Curve (EKC) is also highly relevant to the present work (Brock and Taylor., 2003; Andreoni and Levinson, 2001). In particular, Andreoni and Levinson (2001) who focus on the role of returns to scale in abatement technology in driving the shape of the EKC, also note that the disutility from pollution (hence, damages) may shift the income-consumption-pollution paths. Though clearly pertinent to the present analysis, Andreoni and Levinson (2001) did not concentrate on the role of damages in long-run sustainability considerations.

The remainder of the paper is structured as follows. Section 2 lays out the theoretical model. Section 3 divulges data sources and empirical methods. Section 4 presents results and 5 concludes.

2 Model

Similar to Solow (1956) and Brock and Taylor (2010), we consider a one sector growth model of the form:

$$Y = F(K, BL) \quad (1)$$

where Y is output, F is a concave production function with constant returns to scale which depends on capital (K), labor (L), and productivity (B). We adopt the notation from Brock and Taylor (2010); let n = the growth rate of population, g_B = the rate of productivity growth, and θ is the fraction of output allocated to abatement: $\theta = F_A/F$. Emissions are then described as:

$$E = \Omega F a(\theta) \quad (2)$$

where Ω is the intensity of pollution, or emissions per unit of output, and $a(\theta)$ is a concave abatement function: $a(\theta) = [1 - A(F^A/F)]$. Further, let g_A = exogenous technological progress in abatement. We augment this framework from Brock and Taylor (2010) by introducing monetized pollution damages as shown in (3), where (V) is the marginal damage of pollution emissions.:

$$D = V \Omega F a(\theta) \quad (3)$$

Then, g_V is the exogenous growth rate in marginal damages, which may be influenced by income (capital per worker) and population growth¹. Following Brock and Taylor (2010),

¹While g_V is likely to be endogenous with respect to (k), we assume that g_V is exogenous. Note, assuming exogeneity of g_V does not imply constant damage. Rather, the rate of growth in g_V is exogenous to (k).

we describe output (net of investment in abatement), emissions, and damages, per capita:

$$y = f(k)[1 - \theta] \quad (4)$$

$$e = f(k)\Omega a(\theta) \quad (5)$$

$$d = f(k)V\Omega a(\theta) \quad (6)$$

where $y = Y/BL$, $k = K/BL$, $e = E/BL$, $d = D/BL$, and $f(k) = F(k, 1)$.

Next, we integrate monetary pollution damage into a measure of net per capita output. Let r = the pre-abatement level of damages expressed as a fraction of output, and μ = the elasticity of damages with respect to abatement. Then, net damage, per unit of output, is given by $[r - \mu\theta]$.

This enables an expression of damage-adjusted output:

$$y = f(k)[1 - \theta - [r - \mu\theta]] \quad (7)$$

The rate of change of this adjusted measure of capital per effective worker is shown in (8).

$$\dot{k} = sf(k)[1 - \theta - [r - \mu\theta]] - [\delta + g_B + n]k \quad (8)$$

The rate of change is increasing in the fraction of output available for consumption accumulated through savings (s) (net of investment in abatement and damage) and it is decreasing in population growth (n), productivity growth g_B , and depreciation (δ).

Assuming the production function is Cobb Douglas, $f(k) = k^\alpha$, where α is the capital share of output, which is fixed by assumption. Then, the proportional rate of change in (k), is:

$$\frac{\dot{k}}{k} = sk^{\alpha-1}[1 - \theta - [r - \mu\theta]] - [\delta + g_B + n] \quad (9)$$

Solving the differential equation in (9) yields an expression for the capital per effective

worker at time (t):

$$k(t) = [k^{*(1-\alpha)}(1 - \exp(-\lambda t)) + k(0)^{1-\alpha}\exp(-\lambda t)]^{1/(1-\alpha)} \quad (10)$$

where $k(0)$ is initial capital per effective worker and k^* is the economy's balanced growth path, which is found by setting (9) to zero and solving for: $k^* = (\frac{s(1-\theta-[r-\mu\theta])}{\delta+g_B+n})^{1/(1-\alpha)}$. As in Brock and Taylor (2010), $k(t)$ is a weighted-average of $k(0)$ and k^* . Further, $\lambda = (1 - \alpha)(\delta + g_B + n)$ is the speed of the economy's adjustment between the initial and balanced growth path. Note that the introduction of neither emissions nor damage affects this rate of adjustment.

From (2) and (3) we derive the expression for the growth rate of total emissions and damages. To do so, we introduce the following notation from Brock and Taylor (2010); g_E denotes the growth rate of emissions as the economy follows the balanced growth path. Emissions grow according to the difference between technological progress, g_B , population growth (n), and abatement, g_A : $g_E = g_B + n - g_A$.

$$\frac{\dot{E}}{E} = \alpha \frac{\dot{k}}{k} + g_E \quad (11)$$

$$\frac{\dot{D}}{D} = \alpha \frac{\dot{k}}{k} + g_E + g_V \quad (12)$$

The difference between (11) and (12) clearly depends on g_V , the growth rate of marginal damages.² If g_V is positive damages grow more rapidly than emissions. Conversely, if g_V is negative emissions outpace damages. The only situation in which (11) = (12) is if marginal damages are constant.

We next turn to the task of identifying the level of capital per worker at which emissions and damages peak. Conceptually, the position of these maxima relative to the balanced growth path is a critical determinant of an economy's sustainability. Brock and Taylor

²In the case of CO₂, g_V is the growth rate of the social cost of carbon. In the case of local pollutants g_V is the growth of the valuation placed on attributable mortality risk, also called the Value of Statistical Life.

(2010) deem growth sustainable if emissions fall on the balanced growth path. We propose that growth is sustainable when net savings, or changes in capital per worker, inclusive of abatement and damages, is non-negative.

Let T_1 denote the time at which emissions peak ($\dot{E} = 0$) and let T_2 denote the time at which damages peak ($\dot{D} = 0$). We substitute (9) into (11) to obtain:

$$k(T_1) = \left(\frac{s(1 - \theta - [r - \mu\theta])}{\delta + g_B + n - \frac{g_E}{\alpha}} \right)^{\frac{1}{(1-\alpha)}} \quad (13)$$

As Brock and Taylor (2010) point out, if $g_E < 0$, then $k(T_1) < k^*$ and emissions fall at k^* . In contrast, if $g_E > 0$, then $k(T_1) > k^*$ and emissions rise at k^* . Therefore, Brock and Taylor (2010) deem growth sustainable if $g_E < 0$.

We substitute (9) into (12) which yields:

$$k(T_2) = \left(\frac{s(1 - \theta - [r - \mu\theta])}{\delta + g_B + n - \frac{(g_E + g_V)}{\alpha}} \right)^{\frac{1}{(1-\alpha)}} \quad (14)$$

How damages affect inferences about sustainability hinges on a comparison of (13) and (14). This comparison is the central conceptual contribution of the paper and it hinges on g_V . Empirical evidence suggests that $g_V > 0$, provided real positive income growth (Robinson and Hammitt, 2009; Hammitt and Robinson, 2011; IWG, 2013). This implies that $T_2 > T_1$; damages peak at a higher capital per worker level than emissions. This result has critical implications for inferences about sustainable growth. We evaluate sustainability at k^* , where $\frac{\dot{k}}{k} = 0$. Hence, by (12), sustainable growth requires that the growth rate of abatement must counteract the growth in emissions and the growth in marginal damages. That is, damages must be weakly falling: $g_A \geq g_B + n + g_V$. Since $\frac{\dot{k}}{k} = 0$, rising damage reduces net consumption. This violates the welfare-based definition of sustainability. Also note that by definition at k^* , g_V for local pollutants (the VSL) is zero because income is unchanged at k^* . From (12), at k^* , damages from air pollution grow at g_E . For CO_2 , g_V is growth in the social cost of carbon. At k^* , g_V may be positive because the SCC is determined by the

atmospheric stock of CO₂ rather than real income growth. Therefore (12) implies that even at k^* damages from CO₂ may still be rising even if $g_E \leq 0$.

In certain cases, the distinction between emission and damage-based sustainability may be innocuous. For example, if $k(T_1) < k(T_2) < k^*$, then growth is sustainable under either definition. Conversely, if $k(T_1)$ and $k(T_2)$ exceed k^* , then growth is unsustainable under either definition. In contrast, if $k(T_1) < k^* < k(T_2)$, then focusing on emissions would lead to the erroneous conclusion that growth is sustainable. In this case, emissions fall, but damages rise without limit as the economy approaches k^* . Accordingly, net savings is negative because $\frac{\dot{k}}{k} = 0$. And, as argued by Hamilton (1994, 1996), such an outcome cannot be sustainable.

Table 1 displays the differences in the characterizations of the balanced growth path in Solow (1956), Brock and Taylor (2010), and the present paper. The innovation from Brock and Taylor (2010) relative to Solow (1956), was the inclusion of abatement expenditures (θ) which necessarily reduces k^* , the steady state income level. We further augment net savings by including damages, as shown in the bottom-left cell of Table 1. This further reduces k^* . Comparing $k(T_1)$ from Brock and Taylor (2010) to equation (13), both shown in the middle column of Table 1, reveals that including damage in (7) lowers $k(T_1)$ in (13), relative to $k(T_1)$ in Brock and Taylor (2010). We contend that this is the preferred measure of net savings because it facilitates the definition of sustainable growth invoked above.

Table 1: Capital per effective worker at turning points.

Paper	k^*	$k(T_1)$	$k(T_2)$
Solow (1956)	$(\frac{s}{\delta+g_B+n})^{\frac{1}{1-\alpha}}$	-	-
Brock and Taylor (2010)	$(\frac{s(1-\theta)}{\delta+g_B+n})^{\frac{1}{1-\alpha}}$	$(\frac{s(1-\theta)}{\delta+g_B+n-\frac{g_E}{\alpha}})^{\frac{1}{1-\alpha}}$	-
This paper	$(\frac{s(1-\theta-[r-\mu\theta])}{\delta+g_B+n})^{\frac{1}{1-\alpha}}$	$(\frac{s(1-\theta-[r-\mu\theta])}{\delta+g_B+n-\frac{g_E}{\alpha}})^{\frac{1}{1-\alpha}}$	$(\frac{s(1-\theta-[r-\mu\theta])}{\delta+g_B+n-\frac{(g_E+g_V)}{\alpha}})^{\frac{1}{1-\alpha}}$

3 Data

This section describes data sources and computational methods for CO₂ and PM_{2.5} damages. It concludes with a discussion of the integration of damages into the NIPAs.

CO₂ emissions are obtained from the Emission Database for Global Atmospheric Research (EDGAR), (Crippa et al., 2019). To compute monetary damages from CO₂ emissions we use the social cost of carbon (SCC), which is the marginal damage per ton of CO₂ emitted. Estimates of the SCC vary widely in the literature. We use estimates from the US Government’s Interagency Working Group (IWG) study (IWG, 2013) which provides estimates of the SCC for 2010-2050 every five years. We compute the SCC for relevant years in our dataset by deriving the year on year growth rate. We use a central estimate of \$36 (in 2007 dollars) in 2015 which corresponds to the 3% discount rate. We also perform sensitivity analysis employing a high damage scenario which implies significantly higher values for the SCC. The SCC is uniform across countries because CO₂ is a globally-mixed pollutant. Damages from CO₂, denoted ($D_{i,t}^C$), for country i in year t are the product of marginal damages and emissions:

$$D_{i,t}^C = E_{i,t}^C * SCC_t \quad (15)$$

Although exposure to air pollution is associated with a number of adverse health and productivity impacts, this analysis computes the monetary damage from attributable mortality risk associated with PM_{2.5} exposure. We focus on this health endpoint because prior research shows that it comprises the majority of pollution damage (EPA, 1999, 2011; Muller, Mendelsohn and Nordhaus, 2011). The key data sources for these calculations include the following. Air pollution estimates as population weighted annual average PM_{2.5} concentration for country and year are obtained from a combination of model output, satellite observations, and ground-based measurements following Hammer et al. (2020); Van Donkelaar et al. (2016). In addition to the PM_{2.5} concentrations, we employ global data for baseline mortality risk

and population (Global Burden of Disease Collaborative Network, 2018).³

The calculation of damage from PM_{2.5} begins with the estimation of the relative risk from PM_{2.5} exposure. The relative risk is a function of the PM_{2.5} concentration and it is calculated through the integrated exposure response (IER) function, which is widely used in international assessments of mortality risk from PM_{2.5} exposure (Cohen et al., 2017; Burnett et al., 2018).

$$IER_{j,k,i,t}(PM_{i,t}) = 1 + \alpha_{j,k} * (1 - e^{-\beta_{j,k}(PM_{i,t}-PM_{cf})^{\gamma_{j,k}}}) \quad (16)$$

where $\alpha_{j,k}$, $\beta_{j,k}$, and $\gamma_{j,k}$ are statistically-estimated parameters⁴, $PM_{i,t}$ is the level of PM_{2.5} concentration for country (i) in year (t), and PM_{cf} the theoretical minimum risk exposure level below which no risk is assumed. The subscript (j) denotes the cause of death, which includes stroke, lower respiratory infections, diabetes, chronic obstructive pulmonary disease, ischemic heart disease, and lung cancer. The subscript (k) denotes age group. The IER function was fitted by estimating the parameters $\alpha_{j,k}$, $\beta_{j,k}$, $\gamma_{j,k}$, and PM_{cf} using the methodology described in Cohen et al. (2017). The contributed risk is:

$$PAF_{j,k,i,t} = 1 - \frac{1}{IER_{j,k,i,t}(PM_{i,t})} \quad (17)$$

where PAF is the pollution attributable fraction, i.e. the risk contributed from PM_{2.5} exposure. Note that if $PM=PM_{cf}$, $IER = 1$, then the contributed risk is 0 (there is no additional risk from PM_{2.5} exposure).

Attributable excess mortality from exposure is estimated by evaluating (16) and (17) using the country and year specific ambient PM_{2.5} data, and then computing the product of (17) and age group (k) and cause (j) specific baseline mortality rates Λ along with the

³Data across all five variables - GDP, CO₂ emissions, PM_{2.5}, baseline mortality risk, and population - is available for a total of 163 countries between 1998-2017. Further, given that data for GDP, CO₂ emissions, and PM_{2.5} is also available for 2018, we produce provisional results for 2018 using 2017 baseline mortality risk and population data.

⁴Note that the age group specific IER only applies to stroke and ischemic heart disease (Cohen et al., 2017; Burnett et al., 2018)

relevant population age groups for each end point. Excess mortality ΔM attributable to $PM_{2.5}$ for country (i) in year (t) can then be expressed as:

$$\Delta M_{i,t} = \sum_{j=1}^j \sum_{k=1}^k PAF_{j,k,i,t} * \Lambda_{j,k,i,t} * Population_{j,k,i,t} \quad (18)$$

Calculating monetary damage requires the application of the VSL to the estimated $PM_{2.5}$ -attributable excess mortality.

$$D_{i,t}^P = \Delta M_{i,t} * VSL_{i,t} \quad (19)$$

where $VSL_{i,t}$ is the value of statistical life (VSL) for country (i) in time (t). For the U.S., we employ the U.S.EPA's VSL of \$7.4 million (\$2006) and run a sensitivity for a VSL of \$2.8 million (\$2000) based on contingent valuation studies (Kochi, Hubbell and Kramer, 2006). Most countries do not use VSLs in environmental regulatory analyses. As such, we lack government-endorsed, or official VSLs for applications in most countries aside from the U.S. We estimate VSLs for other countries based on VSL-income elasticities from the literature. Country-by-year income data for 1998 to 2018 are obtained from the World Bank (World Bank, 2019).

The particular elasticities employed depend on country income levels. Robinson and Hammitt (2009), Hammitt and Robinson (2011), and Cropper and Sahin (2009) have argued that higher elasticities are more appropriate for lower income countries. Estimates from stated preference studies also suggest that the VSL-income elasticity is higher in lower income countries. Masterman and Viscusi (2018), for instance, find an income elasticity of 0.55-0.85 for higher income countries and 1.0 for lower income nations. Narain and Sall (2016) suggest an elasticity of 0.8 for high income economies and 1.2 for low and middle income countries. These elasticities were subsequently used in Rauner et al. (2020). We follow this latter parameterization of the VSL-income elasticity. One justification for adopting this approach is that it was endorsed by the World Bank. If countries around the world produced integrated environmental and economic accounts, they would likely do so in accordance

with international standards which might include this guidance from the World Bank. In a sensitivity analysis, we set the VSL-income elasticity to unity for all countries. Finally, within a country, the VSL is held fixed cross-sectionally as is standard practice (EPA, 1999; Shindell et al., 2012).

The VSL for country i in 2006 is:

$$VSL_{i,2006} = \left(\frac{Income_{i,2006}}{Income_{US,2006}} \right)^{\eta_{i,2006}} * VSL_{US,2006} \quad (20)$$

and then,

$$VSL_{i,t} = \left(\frac{Income_{i,t}}{Income_{i,2006}} \right)^{\eta_{i,t}} * VSL_{i,2006} \quad (21)$$

where η is the VSL-income elasticity.

Having estimated air pollution and CO₂ damages, we integrate these values into the national income and product accounts as follows. We calculate EVA as GDP less damages (Muller, 2020, 2014). GDP for each country from 1998 to 2018 in constant 2010 USD⁵ is obtained from the World Bank (World Bank, 2018).

$$EVA_{i,t} = GDP_{i,t} - D_{i,t}^P - D_{i,t}^C \quad (22)$$

The conceptual justification for this treatment of damages is provided in Nordhaus (2006) and Abraham and Mackie (2006).

4 Results

The results begin with a global comparison of EVA and GDP growth. Next is an exploration of the rates of growth in EVA and GDP among the eight largest economies in the world. The relative rates of growth in EVA and GDP depend critically on changes in the pollution

⁵Note that VSL values in USD 2006 and SCC values in USD 2007 are converted to USD 2010 prices using inflators from the Consumer Price Index (CPI).

intensity of output, which is also discussed below. In the third subsection, the scope of the analysis is expanded to include all countries grouped by income class. Next the analysis covers BRICS: Brazil, Russia, India, China, and South Africa. The fifth subsection conducts assessment of the relationship between emissions, monetary damages, and GDP per capita which links the empirical and conceptual models. We conclude with a brief summary from the sensitivity analysis.

4.1 Global Growth Comparison

Globally, from 1998 to the Great Recession, EVA outpaced GDP growth. This difference began between 20 and 30 basis points. This positive spread suggests that the global economy was becoming less pollution intensive. However, by 2010, the EVA and GDP growth rates were equivalent. After 2015, global GDP growth exceeded EVA by 5 to 10 basis points. These results are shown in Appendix figure A1. We next examine results for specific countries.

4.2 Pollution Intensity in the Largest Economies

Figure 1 examines the growth rates of EVA and GDP for the eight largest economies in the world (as measured by GDP). For the U.S., EVA growth has generally outpaced GDP growth. Figure 2 shows why this is the case. The U.S. damage-to-output ratio fell from about 10% in 1998 to 6% in 2018. This reduction was partially due to environmental regulatory constraints as well as market forces including the rise of cheap natural gas and the resulting displacement of coal-fired capacity in the electricity generation sector (Muller, 2020; Holland et al., 2020). Prior to the Great Recession, EVA growth exceeded GDP growth by about 30-40 basis points. Since then, the rate differential is considerably smaller. This finding comports with earlier estimates of EVA and GDP growth in the U.S. (Muller, 2014, 2020). Figures A2 and A3 in the appendix plot ambient $PM_{2.5}$ and CO_2 emissions. In the U.S., CO_2 emissions peaked just prior to the Great Recession. Ambient $PM_{2.5}$ fell consistently from 1998 to 2018.

Figure 1: 5 year rolling averages of EVA-GDP Growth Rates for the world's eight largest economies by GDP (1999-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

For China, the world's second largest economy, the results look very different. The 1998 to 2018 period was transformative for China. Real GDP per capita grew by a factor of five. This meteoric income growth had well known implications for the physical environment. $PM_{2.5}$ increased by nearly 50% for the first 15 years of the analysis, and fell thereafter (see figure A2). Likewise, CO_2 emissions climbed rapidly until 2011, when the rate of increase declined (figure A3). Figure A4 reports that real GED increased by nearly a factor of seven from 1998 to 2018. The rate of increase in GED fell slightly in 2011, when ambient $PM_{2.5}$ fell and CO_2 emission growth slowed. This rise in GED was a function of the more than seven fold increase in the marginal value of mortality risk or the VSL (Figure A5).

With a seven fold increase in GED and a five fold increase in GDP, China's economy became more pollution intensive. Figure 2 confirms this. In 1998, GED amounted to under

11 percent of GDP. By 2011, GED climbed relative to GDP such that pollution intensity topped 13 percent. After the Great Recession, GED-to-GDP plateaued. This corresponds to the period of falling ambient $\text{PM}_{2.5}$ levels and deceleration in CO_2 emission growth.

The rapid ascent in environmental pollution damage in China significantly affected apparent growth rates. China's GDP growth outpaced EVA by between 25 and 50 basis points prior to 2011. This corresponds to when pollution intensity was rising. After 2012, pollution intensity started to fall in China, and EVA growth modestly surpassed GDP.

Also in Asia, Japan exhibited much smaller differences between EVA and GDP growth. Contributing to this small difference were nearly constant ambient $\text{PM}_{2.5}$ levels and CO_2 emissions (see figures A2 and A3). The EVA - GDP spread was negative on average. Figure 2 shows that damages were about 7% of GDP in 1998 and grew to just under 8% in 2018.

We next turn to the largest European economies. Early in the sample period, prior to 2005, German EVA grew more rapidly than GDP by between 50 and 100 basis points on average. The EVA-GDP growth differential then rapidly attenuated, falling to near zero after 2005. Figure 2 indicates that pollution damage amounted to about 13% of GDP in 1998. Pollution intensity fell to under 9% by 2007. It remained at roughly this level until 2018.

In the U.K. EVA consistently outpaced GDP growth. Prior to 2005, EVA growth exceeded GDP growth by between 50 and 100 basis points on average. After the Great Recession, EVA expansion fell relative to GDP such that the rates were roughly equal toward the end of the sample period. Figure 2 demonstrates that pollution intensity in the U.K. fell very rapidly from about 14% in 1998 (similar to Germany) to 9% in 2004. The damage to output ratio in the U.K. continued to drop to under 7% in 2018. Over this 21 year period, pollution intensity in the U.K. fell by one-half. The continued decline in pollution intensity from 2005 to 2018 stands in stark contrast to the persistently higher damage to GDP ratio in Germany after 2005.

In France, EVA and GDP growth were quite similar from 1998 to 2018. France is highly

dependent on nuclear energy and has generally low air pollution and CO₂ emissions per unit GDP. Because of this, as depicted in figure 2, its GED-to-GDP ratio in 1998 was much lower than that of either the U.K. or Germany. And, without the rapid reduction in pollution intensity observed in the U.K. and Germany, EVA and GDP growth rates did not diverge as much.

Italy's results bear similarities to the German economy. Prior to the financial crisis, EVA growth tended to exceed GDP growth as GED-to-GDP fell from 11% to 9%. However, in the last years of the sample, the EVA-GDP growth differential has converged because pollution intensity did not continue to fall.

Figures A2 and A3 report emissions and ambient pollution levels in the European economies included in figures 1 and 2. In each of these countries, CO₂ emissions fell, but very slowly. Likewise, ambient PM_{2.5} fell from average values in 1998 of around 20 $\mu\text{g}/\text{m}^3$. The degree of decline essentially explains the growth differentials in figure 1. That is, the U.K. exhibits the steepest decline in ambient PM_{2.5}, whereas the levels in Germany and Italy remained higher.

Whereas China's economy grew rapidly more pollution intensive and then began to show evidence of leveling off, India presents a case of a large developing economy just beginning to increase in pollution intensity. From 1998 to 2004, EVA and GDP growth were roughly equivalent. After 2004, GDP per capita began to accelerate ultimately doubling by 2018. Well-documented pollution problems ensued. Figure A2 reports just how rapid the growth in ambient pollution was; PM_{2.5} levels increased from about 50 $\mu\text{g}/\text{m}^3$ in 2005 to almost 80 $\mu\text{g}/\text{m}^3$ in 2012. GED increased by a factor of three from 2005 to 2018 (figure A4). Accordingly, figure 2 demonstrates a steady increase in the pollution intensity of the Indian economy from under 8% in 2005 to over 10% in 2018. The result of this was that EVA growth dipped below GDP by as much as 50 basis points after 2005.

Summarizing the results in figures 1 and 2, suggests that there are essentially two patterns at work. In the U.S. and the Western European economies, pollution intensity fell. These

Figure 2: GED/GDP for the world's eight largest economies economies by GDP (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

results are consistent with the analysis of Le Quéré et al. (2019) who show that reductions in CO₂ emissions have been driven by an increase in renewable energy and a fall in energy use. Among these economies, pollution intensity fell the most in the U.K. For the U.S. and Western Europe, most of the reductions in pollution intensity occurred from 1998 to 2005. All of these countries have essentially constant pollution intensity from 2010-2018, after the Great Recession.

In China, India, and Japan, pollution intensity increased. China, while exhibiting a rapid increase in damage intensity up to 2015, appears to be transitioning to a phase in which pollution damages are falling relative to GDP. India, however, just began to exhibit signs of rising pollution intensity in 2005. It is important to note that because of the geographic justification of Japan with respect to China and South Korea, it is likely that some of the rise in pollution damages is due to transboundary flows of PM_{2.5} constituents from China

and South Korea eastward into Japan.

Results for eight other members of the G20 group of nations are shown in figures A6 and A7.

4.3 Pollution Intensity by Income Group

While the preceding analysis focuses on the eight largest economies in the world, figure 3 groups all countries according to income status⁶ and it displays the GDP-weighted GED to GDP ratios. The top-left panel shows that high income countries have had declining pollution intensities from about 10 percent to 7 percent of GDP. This aggregate result is in accord with the results for the high income countries shown in figure 2. Appendix figure A8 shows average GDP per capita growth rates. High income countries exhibited growth of about 2% from 1998 to 2008, near zero from 2008 to 2011, and 1% thereafter. In high income countries there was a steady rate of decline in damage intensity despite significant variation in income growth over the business cycle.

For economies in the European Union (EU) GED declined from 11 percent of GDP in 1998 to 7 percent in 2018. We also report that for countries in the EU Emissions Trading Scheme (EU ETS), a cap-and-trade program limiting CO₂ emissions, GED-to-GDP declined from about 9 percent in 2005 (the start of the EU ETS) to 7 percent in 2018.

The top-right panel of the figure highlights upper-middle income countries. In short, pollution intensity of these nations, which includes China, increased from over 7% in 1998 to almost 10% in 2018. The increase in pollution intensity was quite steady, with a slight reduction in trend over the Great Recession. In Figure A9, shown in the appendix, we recreate this graph without China. The remaining countries in the upper-middle income group essentially had flat pollution intensity of about 6-7% between 1998 and 2018. The comparison of figures 3 and A9 highlights the extent to which China is an outlier. No other

⁶Countries are grouped according to their income status in 2018. Graphing according to current year income status produced odd results when large countries such as China moved out of the lower middle income group to the higher middle income group.

Figure 3: GDP weighted GED/GDP for different income groups (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

large economy grew in pollution intensity like China. And, because of the magnitude of the Chinese economy, this has clear ramifications for global sustainability.

In contrast to the upper middle income countries, the lower middle income countries exhibit a very gradual increase in pollution intensity, rising from 7% of GDP in 1998 to about 8% in 2018. India is included in this group. As such, some portion of the post 2004 increase in pollution intensity stems from the substantial pollution intensification of the Indian economy.

Along the four income groups in figure 2, low income economies show the lowest pollution intensity of output. The GED remain at roughly 4% of GDP from 1998 to 2018. Figure A8 indicates that these countries experienced GDP growth beginning at about 1% in 1998 and rising to about 3% in 2005. GDP growth held at roughly that rate for the remainder of the sample. The steady damage-to-output ratio suggests that these countries have neither

invested in abatement nor have they embarked on development trajectories of the sort evinced in China and India where growth in real output stimulates greater pollution intensity.

A review of the results in figure 3 provides a useful perspective on how the pollution intensity of output changes over the development trajectory of the world’s economies. As noted above, pollution damage intensity as a share of GDP was consistently lowest among nations with very low per capita income levels. For nearly the entire 21-year period from 1998 to 2018, damage intensity in the lower middle income category was consistently two times greater than the low income countries. The gap between pollution intensity in the lower middle and upper middle groups was essentially zero in 1998. However, over the next 21 years, pollution intensity levels in the lower middle and upper middle income groups diverged as China’s GDP and GED-to-GDP ratios increased substantially.

Next, the 10% GED-to-GDP ratio in the high income countries in 1998 was higher than the intensity level in both middle income groups at that time. However, by 2018, pollution intensity was lower in the high income group than both the upper middle and low middle income countries.

So, in 1998 pollution intensity increased with income levels; from 4% to 7% to 10% up the income scale. However, in 2018, this monotonically-increasing relationship between pollution intensity and per capita GDP broke down. In 2018, pollution intensity increased with income, up to a point, and then fell at the highest income levels. The emergent, non-monotonic, or inverted "U-shaped" relationship between damage intensity and income is suggestive of an EKC. We return to this topic in more detail in Section 4.5.

4.4 BRICS

We next turn to an analysis of the five major emerging economies often referred to as ‘BRICS’: Brazil, Russia, India, China, and South Africa. These economies are often grouped together because of their emerging status and likely importance for global growth outcomes. Figures A10, A11, and A12 in the appendix summarize the results for these countries. Figure

A10 displays the real per capita GDP indexed to the 1998 values. As is well known, China’s real per capita income increase by more than five-fold between 1998 and 2018. Russia and India enjoyed more than a doubling of real incomes, while Brazil and South Africa exhibit an increase of 25 and 40 percent respectively. These varied growth outcomes mapped into equally heterogeneous pollution damage growth. Figure A11 shows that GED in China increased by nearly seven times. India’s GED increased by five times. The GED in South Africa, Russia, and Brazil all roughly doubled. Figure A12 displays the indexed pollution intensity in these five nations. First, China and India have incurred increases in pollution intensity of about 30 percent and 16 percent from 1998 to 2018, respectively. However, while China’s pollution intensity increased beginning shortly after the year 2000, India’s did not increase until after 2005. Brazil and South Africa have essentially flat pollution intensity. In contrast to the other countries, Russia shows no consistent change in pollution intensity until after the Great Recession, when damage-to-output fell by about 10%. The analysis of BRICS conveys two conclusions. First, China and India exhibited large increases in per capita GDP but also in GED intensity, though the timing of these increases differ markedly. Second, the experiences in Brazil, South Africa, and Russia are notably different. Though Russia’s real income doubled, its pollution intensity fell. As a result EVA growth was consistently higher than conventional growth between 2005-2013 (figure A13). In South Africa and Brazil, pollution intensity was at the same level in 1998 and 2018 despite significant increases to real income.

4.5 Environmental Kuznets Curve

This section tests the predictions of the conceptual model that physical emissions maximize at lower levels of income than damages. We treat $PM_{2.5}$ concentrations as a proxy for emissions of $PM_{2.5}$ and its precursors, since $PM_{2.5}$ concentrations are more precisely defined and measured than emissions, and since $PM_{2.5}$ concentrations and emissions are closely related. Figure 4 plots measures of emissions of CO_2 , population weighted average ambient

concentrations of $\text{PM}_{2.5}$, and monetary damages, for each country-year pair, against real per capita GDP. Figure 4, which displays flexible cubic splines fit to the data, provides empirical support for the predictions of the conceptual model. Beginning with $\text{PM}_{2.5}$ concentration, figure 4 shows that concentrations for countries at very low income levels are very high, nearly $40 \mu\text{g}/\text{m}^3$. Concentrations then fall rapidly with income before exhibiting a local maximum around \$20,000 income levels. Thereafter, $\text{PM}_{2.5}$ levels fall as income grows. CO_2 emissions, in contrast, rise rapidly with income at income levels under \$20,000. Emissions then level off, continuing to rise, but at a slower rate. Monetary damages also rise rapidly at low income levels. In contrast to CO_2 emissions, damages continue to rise rapidly with income.

Figure 4: EKC curve showing emissions peaking earlier than damages. The brown line in the plot is population weighted average ambient $\text{PM}_{2.5}$ concentration and the blue line is CO_2 emissions per capita. The red line is GED/capita as measured on the secondary Y axis on the right.

To further explore the relationship between income levels and CO_2 emissions, figure A14 plots quadratic fits for damages and CO_2 emissions. This exercise provides compelling support for the predictions of the conceptual model. CO_2 emissions maximize at about 15

tons per capita, per year at an income level of about \$70,000. In contrast, monetary damages peak at an income level of about \$130,000. The per capita damage at the apex is roughly \$5,000. Figure A14 does not plot the $PM_{2.5}$ concentrations because the relatively inflexible quadratic form proves to be a poor fit to the data.

While the preceding analysis reports an aggregate EKC for the global economy, perhaps most important are the results for China. Figure A2 reports that ambient levels of $PM_{2.5}$ peaked in 2011. Emissions of CO_2 , while increasing, have slowed considerably (figure A3). Yet, as figure A4 reports, monetary damages increased 50% since 2011 and have averaged an annual growth rate of 5%. These comparisons, for the world's second largest economy, highlight the importance of an assessment of sustainability based on monetary damage rather than physical units of pollution.

4.6 Sensitivity Analysis

Though by no means comprehensive, this sensitivity analysis covers the key parameters in our GED and EVA calculations. We begin with an alternative VSL. In the default case, the VSL for the U.S. is \$7.4 million, we employ \$2.8 million based on a review of contingent valuation studies ((Kochi, Hubbell and Kramer, 2006). The procedures used to extrapolate this value to countries other than the U.S. is identical to that employed in the default case. Figure A15 indicates that this permutation attenuates the difference between EVA and GDP growth rates. The sign of the difference is essentially unaffected. That is, the U.S. and European economies exhibit positive growth differentials, while China and India show predominantly negative growth spreads. Similarly, figure A16 indicates that the lower VSL results in lower levels of pollution intensity. Figure A17 plots the relationships between ambient $PM_{2.5}$, CO_2 emissions, GED, and income. The results are consistent with figure 4. Namely, $PM_{2.5}$ maximizes at low income levels, whereas GED and CO_2 continue to rise. And, the slope of the GED is considerably steeper than CO_2 emissions.

In the next set of assumptions, we adopt a value of the VSL-income elasticity of unity

for all countries in all years. Figure A18 demonstrates that this change does not fundamentally overturn the EVA-GDP growth differentials. The U.S. and European countries exhibit positive and declining EVA-GDP growth spreads. We note however that in Germany after 2012, GDP exceeds EVA growth. The patterns in China and India are also quite similar to the default case. Figure A19 indicates that, for China, the unit elastic assumption results in a GED-to-GDP ratio of over 15% toward the end of the sample. Recall that under the default assumptions, high income countries have a VSL-income elasticity of 0.8. Because real incomes have generally increased in these countries, and the marginal damages for $\text{PM}_{2.5}$ rise more rapidly with an elasticity of 1, the high income economies exhibit slower declines in pollution intensity in figure A19. Figure A20 shows that the effect of this change on the EKC graphs is essentially to steepen the GED plot, which does not overturn our earlier conclusion that the GED peak later than emissions.

Finally, we employ a higher SCC applied to CO_2 emissions. Figure A21 demonstrates that this alternative appreciably affects the growth differentials in some of the eight largest economies. For example, the EVA-GDP growth differential reaches -1% for China in 2004, before rising rapidly back to nearly zero in 2012 and +0.5% in 2017. In India, the average growth rate spread falls to -0.6% in 2010. In Germany and the U.K., the EVA-GDP difference is larger than in the default case. Figure A22 shows that the higher SCC has a significant effect on pollution intensity. The GED-to-GDP ratio tops 20% in China and nears 20% for India late in the sample. Pollution intensity was around 15% in 1998 in Germany and the U.K.. The effect on the EKC graphs is minimal (figure A23). Again, the GED plot steepens, which supports the predictions of the conceptual model.

5 Conclusion

This analysis makes two contributions to the existing literature at the intersection of economic growth and the environment. First, we offer an important extension to the Green

Solow Model proposed by Brock and Taylor (2010). The augmentation consists of redefining output to include environmental pollution damage. Prior papers in this space argue that sustainability hinges on whether emissions are rising or falling at the balanced growth path. In contrast, we contend that what matters for sustainability is whether damages are rising or falling. This position reflects an argument traced back to definitions of sustainability in the neoclassical growth and green accounting literatures; in order for an economy to be growing sustainably, net savings growth (inclusive of natural and physical capital) must be non-negative (Hamilton, 1994, 1996). Thus, since at the balanced growth path, net savings growth is zero, damages must be non-positive to achieve sustainable growth. The consideration of damage-based (rather than emission-based) sustainability is most critical when emissions fall and damages continue to rise at the balanced growth path. In this case, environmental policymakers focused on emissions would erroneously conclude an economy was on a sustainable path.

The paper also contributes the first globally-comprehensive set of environmental accounts for two economically important pollutants over a 21 year time period. This exercise capitalizes on a newly available database of ambient pollution readings along with a comprehensive set of CO₂ emissions data. The empirical analysis reports four key findings. First, high income countries have been on a cleaning-up trajectory since 1998. Our key measure of environmental performance, the GED-to-GDP ratio, fell among these countries from nearly 10% in 1998 to under 7% in 2018. Second, the upper-middle income group exhibited a sharp rise in pollution intensity from over 7% in 1998 to almost 10% in 2018. We are careful to note that the Chinese economy essentially drove this increase. Without China, these upper-middle income countries exhibited very little growth in their damage-to-output ratios. Third, pollution damages comprise the lowest share of output for nations in the lowest income class. Damages remain at about 4% of GDP from 1998 to 2018. This level of pollution intensity comprises about one-half of that in low-middle countries (which includes India). Fourth, our empirical estimation of the EKC for physical emissions and concentrations, when contrasted

to damages, provides firm empirical support for the predictions of the conceptual model. An EKC fit to physical measures of pollution maximizes at lower income levels than one fit to monetary damage. This, as argued above, has potentially critical implications for inferences about society's sustainability. Most importantly, when we analyze emissions, concentrations, and monetary damages in China, we find a case where one might draw such conflicting views on its sustainability. Ambient concentrations of $\text{PM}_{2.5}$ peaked in 2011. The rate of CO_2 emission growth has also fallen recently. Yet, damages continue to rise, having gone up 50% in real terms since 2011. China is a globally relevant case highlighting the salience of our damage-based sustainability measure.

The implications of revisions to national growth estimates are potentially broad and far-reaching. Expectations about growth inform decisions made by central banks in setting monetary policy, investors' choices regarding capital allocations, and, not least, consumer sentiment. Adjustments to relative growth across countries has the potential to permute capital flows, exchange rates, and ultimately, international relations such as multi-lateral trade agreements. Thus, while our focus is on adjusting the traditional economic accounts to recognize external pollution damages, we argue that the ramifications of doing so are, indeed, fundamental to our estimates of growth and economic development.

References

- Abraham, Katharine G, and Christopher Mackie. 2006. “A framework for nonmarket accounting.” In *A new architecture for the US national accounts*. 161–192. University of Chicago Press.
- Andreoni, James, and Arik Levinson. 2001. “The Simple Analytics of the Environmental Kuznets Curve.” *Journal of Public Economics*, 80: 269 – 286.
- Bartelmus, Peter. 2009. “The cost of natural capital consumption: Accounting for a sustainable world economy.” *Ecological Economics*, 68(6): 1850–1857.
- Brock, William A., and M. Scott Taylor. 2003. “The Kindergarten Rule of Sustainable Growth.” *National Bureau of Economic Research*., WP 9597.
- Brock, William A, and M Scott Taylor. 2010. “The green Solow model.” *Journal of Economic Growth*, 15(2): 127–153.
- Burnett, Richard, Hong Chen, Mieczysław Szyszkowicz, Neal Fann, Bryan Hubbell, C Arden Pope, Joshua S Apte, Michael Brauer, Aaron Cohen, Scott Weichenthal, et al. 2018. “Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter.” *Proceedings of the National Academy of Sciences*, 115(38): 9592–9597.
- Cohen, Aaron J, Michael Brauer, Richard Burnett, H Ross Anderson, Joseph Frostad, Kara Estep, Kalpana Balakrishnan, Bert Brunekreef, Lalit Dandona, Rakhi Dandona, et al. 2017. “Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015.” *The Lancet*, 389(10082): 1907–1918.
- Crippa, M, G Oreggioni, D Guizzardi, M Muntean, E Schaaf, E Lo Vullo, E Solazzo, F Monforti-Ferrario, JGJ Olivier, and E Vignati. 2019. “Fossil CO₂ and GHG emissions of all world countries.” *Luxemburg: Publication Office of the European Union*.
- Cropper, Maureen L, and Sebnem Sahin. 2009. *Valuing mortality and morbidity in the context of disaster risks*. The World Bank.
- Domar, Evsey D. 1946. “Capital expansion, rate of growth, and employment.” *Econometrica, Journal of the Econometric Society*, 137–147.
- EPA. 1999. “The Benefits and Costs of the Clean Air Act 1990 to 2010: EPA Report to Congress.”
- EPA. 2011. “The Benefits and Costs of the Clean Air Act from 1990 to 2020: Final Report, Rev. A.”
- Global Burden of Disease Collaborative Network. 2018. “Global Burden of Disease Study 2017 (GBD 2017) Results.”
- Hamilton, Kirk. 1994. “Green Adjustments to GDP.” *Resources Policy*, 155–168.
- Hamilton, Kirk. 1996. “Pollution and Pollution Abatement in the National Accounts.” *Review of Income and Wealth*, 13 – 33.
- Hammer, Melanie S, Aaron van Donkelaar, Chi Li, Alexei Lyapustin, Andrew M Sayer, N Christina Hsu, Robert C Levy, Michael Garay, Olga Kalashnikova, Ralph A Kahn, et al. 2020. “Global Estimates and Long-Term Trends of Fine Particulate Matter Concentrations (1998–2018).” *Environmental Science & Technology*.
- Hammitt, James K, and Lisa A Robinson. 2011. “The income elasticity of the value per statistical life: transferring estimates between high and low income populations.” *Journal of Benefit-Cost Analysis*, 2(1): 1–29.

- Harrod, Roy F. 1939. "An essay in dynamic theory." *The economic journal*, 49(193): 14–33.
- Hartwick, John M. 1977. "Intergenerational Equity and the Investing of Rents from Exhaustible Resources." *American Economic Review*, 67: 972 – 974.
- Holland, Stephen P., Erin T. Mansur, Nicholas Z. Muller, and Andrew J. Yates. 2020. "Decompositions and Policy Consequences of an Extraordinary Decline in Air Pollution from Electricity Generation." *American Economic Journal: Economic Policy*, Forthcoming.
- IWG. 2013. "Technical Support Document:-Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis-Under Executive Order 12866-Interagency Working Group on Social Cost of Carbon."
- Kochi, Ikuho, Bryan Hubbell, and Randall Kramer. 2006. "An empirical Bayes approach to combining and comparing estimates of the value of a statistical life for environmental policy analysis." *Environmental & Resource Economics*, 34(3): 385–406.
- Le Quéré, Corinne, Jan Ivar Korsbakken, Charlie Wilson, Jale Tosun, Robbie Andrew, Robert J Andres, Josep G Canadell, Andrew Jordan, Glen P Peters, and Detlef P van Vuuren. 2019. "Drivers of declining CO₂ emissions in 18 developed economies." *Nature Climate Change*, 9(3): 213–217.
- Mankiw, N Gregory, David Romer, and David N Weil. 1992. "A contribution to the empirics of economic growth." *The quarterly journal of economics*, 107(2): 407–437.
- Mankiw, N Gregory, Edmund S Phelps, and Paul M Romer. 1995. "The growth of nations." *Brookings papers on economic activity*, 1995(1): 275–326.
- Masterman, Clayton J, and W Kip Viscusi. 2018. "The income elasticity of global values of a statistical life: stated preference evidence." *Journal of Benefit-Cost Analysis*, 9(3): 407–434.
- Muller, Nicholas. 2020. "Long-Run Environmental Accounting in the U.S. Economy." In *Environmental and Energy Policy and the Economy*. Vol. 1, 158– 191. University of Chicago Press.
- Muller, Nicholas Z. 2014. "Boosting GDP growth by accounting for the environment." *Science*, 345(6199): 873–874.
- Muller, Nicholas Z, Robert Mendelsohn, and William Nordhaus. 2011. "Environmental accounting for pollution in the United States economy." *American Economic Review*, 101(5): 1649–75.
- Narain, Urvashi, and Chris Sall. 2016. *Methodology for valuing the health impacts of air pollution: discussion of challenges and proposed solutions*. World Bank.
- Nordhaus, William D. 2006. "Principles of national accounting for nonmarket accounts." In *A new architecture for the US national accounts*. 143–160. University of Chicago Press.
- Nordhaus, William D, and Edward C Kokkelenberg. 1999. *Nature's Numbers*. National Academy Press Washington, DC.
- Nordhaus, William D, and James Tobin. 1973. "Is growth obsolete?" In *The measurement of economic and social performance*. 509–564. Nber.
- Rauner, Sebastian, Nico Bauer, Alois Dirnhaichner, Rita Van Dingenen, Chris Mutel, and Gunnar Luderer. 2020. "Coal-exit health and environmental damage reductions outweigh economic impacts." *Nature Climate Change*, 1–5.
- Robinson, Lisa A, and James K Hammitt. 2009. "The value of reducing air pollution risks in sub-Saharan Africa."
- Shindell, Drew, Johan CI Kuylenstierna, Elisabetta Vignati, Rita van Dingenen, Markus

- Amann, Zbigniew Klimont, Susan C Anenberg, Nicholas Muller, Greet Janssens-Maenhout, Frank Raes, et al. 2012. “Simultaneously mitigating near-term climate change and improving human health and food security.” *science*, 335(6065): 183–189.
- Solow, Robert M. 1956. “A contribution to the theory of economic growth.” *The quarterly journal of economics*, 70(1): 65–94.
- Solow, Robert M. 1974. “Intergenerational Equity and Exhaustible Resources.” *Review of Economic Studies*, 41: 29 – 45.
- Tschofen, Peter, Inês L Azevedo, and Nicholas Z Muller. 2019. “Fine particulate matter damages and value added in the US economy.” *Proceedings of the National Academy of Sciences*, 116(40): 19857–19862.
- Van Donkelaar, Aaron, Randall V Martin, Michael Brauer, N Christina Hsu, Ralph A Kahn, Robert C Levy, Alexei Lyapustin, Andrew M Sayer, and David M Winker. 2016. “Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors.” *Environmental science & technology*, 50(7): 3762–3772.
- World Bank. 2018. “GDP (constant 2010 US\$).” <https://data.worldbank.org/indicator/NY.GDP.MKTP.KD>.
- World Bank. 2019. “World Bank Country and Lending Groups.” <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519>.

Appendix

1 Global

Figure A1: EVA and GDP growth rates for the global economy (including all 163 countries) for 1999-2018. The red line shows GDP growth and blue line shows EVA growth. The brown line shows the 5 year rolling average of the difference in growth rates as measured by the secondary Y axis on the right.

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

2 World's Largest Economies by GDP

2.1 Eight Largest Economies

Figure A2: Population weighted annual average ambient $PM_{2.5}$ concentration for the world's eight largest economies (1998-2018).

Figure A3: Carbon dioxide emissions for the world's eight largest economies (1998-2018). Note the different scale for USA and China.

Figure A4: GED indexed such that $GED(1998) = 100$ for the world's eight largest economies (1998-2018).

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A5: Value of Statistical Life for the world's eight largest economies (1998-2018). Note the different scale for China and India.

2.2 Other members of the G20

Figure A6: 5 year rolling averages of EVA-GDP Growth Rates for members of the G20 group of nations (1999-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A7: GED/GDP for members of the G20 group of nations (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

3 Results for Income Groups

Figure A8: GDP Growth Per capita for different income groups as weighted by GDP (1999-2018)

Figure A9: GED/GDP for different income groups as weighted by GDP and without China (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

4 BRICS

Figure A10: GDP/Capita Indexed such that $\text{GDP/Capita}(1998) = 100$ for nations in the BRICS grouping (1998-2018)

Figure A11: GED indexed such that $\text{GED}(1998) = 100$ for nations in the BRICS grouping (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A12: GED/GDP for nations in the BRICS grouping (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A13: 5 year rolling averages of EVA-GDP Growth Rates for nations in the BRICS grouping (1999-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

5 EKC - Quadratic Fit

Figure A14: Quadratic fit for the EKC curve showing emissions peaking earlier than damages. The blue line in the plot is CO₂ emissions/capita. The red line is GED/capita as measured on the secondary Y axis on the right.

6 Sensitivity analysis

6.1 Lower VSL

We perform the analysis based on a VSL value of USD 2.8 million (2000) for the USA.

Figure A15: 5 year rolling averages of EVA-GDP Growth Rates for the world's eight largest economies by GDP (1999-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A16: GED/GDP for the world's eight largest economies by GDP (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A17: EKC curve showing emissions peaking earlier than damages. The brown line in the plot is population weighted ambient PM_{2.5} concentration and the blue line is CO₂ emissions per capita. The red line is GED/capita as measured on the secondary Y axis on the right.

6.2 Unity Elasticity of Income

We perform the analysis using an income elasticity $\eta = 1$.

Figure A18: 5 year rolling averages of EVA-GDP Growth Rates for the world's eight largest economies by GDP (1999-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A19: GED/GDP for the world's eight largest economies by GDP (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A20: EKC curve showing emissions peaking earlier than damages. The brown line in the plot is population weighted ambient PM_{2.5} concentration and the blue line is CO₂ emissions per capita. The red line is GED/capita as measured on the secondary Y axis on the right.

6.3 95th percentile SCC

We use the 95th percentile SCC values which correspond to a high damage scenario for climate change.

Figure A21: 5 year rolling averages of EVA-GDP Growth Rates for the world's eight largest economies by GDP (1999-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A22: GED/GDP for the world's eight largest economies by GDP (1998-2018)

Note: 2018 results are provisional and calculated using 2017 data for population and baseline mortality risk along with 2018 data for PM, carbon emissions and GDP.

Figure A23: EKC curve showing emissions peaking earlier than damages. The brown line in the plot is population weighted ambient PM_{2.5} concentration and the blue line is CO₂ emissions per capita. The red line is GED/capita as measured on the secondary Y axis on the right.