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The Green Solow model

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Abstract We argue that a key empirical finding in environmental economics—the Environmental Kuznets Curve (EKC)—and the core model of modern macroeconomics—the Solow model—are intimately related. Once we amend the Solow model to incorporate technological progress in abatement, the EKC is a necessary by product of convergence to a sustainable growth path. We explain why current methods for estimating an EKC are likely to fail; provide an alternative empirical method directly tied to our theory; and estimate our model on carbon emissions from 173 countries over the 1960–1998 period.

Keywords Environment · Environmental Kuznets Curve · Carbon emissions · Solow model · Sustainability · Pollution

1 Introduction

The goal of this paper is to provide a cohesive theoretical explanation for three puzzling features of the pollution and income per capita data. To do so we introduce the reader to a very simple growth model closely related to the one-sector Solow model and show how this amended model generates predictions closely in line with U.S. and European evidence on emissions, emission intensities and pollution abatement costs. The model provides an explanation for the sometimes confusing and fragile empirical results present in the growth and environment literature, while offering an alternative testing methodology tightly tied to theory. Importantly, it resolves several puzzles related to the Environmental Kuznets Curve

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which is an empirical finding linking rising per capita income levels with a first deteriorating and then improving environment.

While our work is related to recent attempts to explain the Environmental Kuznets Curve (thereafter EKC) it differs in several important ways. First, we attempt to fit more features of the data than just the relationship between pollution emissions and per capita income levels; specifically, we employ data on both pollution abatement costs and emission intensities to argue that key features of the data are largely inconsistent with existing theories. Second, we argue these data are well explained by a very simple variant of the Solow model where technological progress in abatement and diminishing returns to capital play leading roles. By doing so we argue that the forces of diminishing returns and technological progress identified by Solow as fundamental to the growth process, may also be fundamental to the EKC finding. Third, to demonstrate the potential usefulness of our approach we derive an estimating equation directly from theory and evaluate the model using carbon data from 173 countries over the 1960–1998 pre-Kyoto period.

The EKC has captured the attention of policymakers, theorists and empirical researchers alike since its discovery in the early 1990s.[1] The theory literature has from the start focused on developing models that replicate the inverted U shaped relationship. Prominent explanations are threshold effects in abatement that delay the onset of policy, income driven policy changes that get stronger with income growth, structural change towards a service based economy, and increasing returns to abatement that drive down costs of pollution control.[2]

While each of these explanations succeeds in predicting a EKC, they are typically less successful at matching other features of the income and pollution data. One key feature of this data concerns the timing of pollution reductions. Models of threshold effects predict no pollution policy at all over some initial period followed by a period of active regulation.[3] When policy is inactive, emissions are produced in proportion to output. When policy becomes active, the emissions to output ratio declines sharply and immediately aggregate emissions fall. The available data on pollution emissions is however inconsistent with this strong temporal correlation. Emissions per unit output typically decline well before any reduction in aggregate emissions.

A second feature of the data that is difficult to reconcile with many theories is the time series of pollution abatement costs. Theories that rely on rising incomes driving down emissions via tighter pollution policy must square the very large fall in emissions with pollution abatement costs that although rising, appear almost constant as a fraction of overall output. For example U.S. Sulfur Dioxide emissions peaked in 1973 at approximately 32 million tons and fell almost in half to approximately 17 million tons in 2001. Correspondingly large changes in emissions per unit output also occurred. But over much of this period, pollution abatement costs as a fraction of GDP or manufacturing value-added, remained small and, most importantly, without much of a positive trend. Theories that rely on tightening environmental policy predict ever increasing costs of abatement, since emissions per unit of output must fall faster than aggregate output to hold pollution in check. In a world without technological progress in abatement, this requires larger and larger investments in pollution control.[4]

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[1] See Grossman and Krueger (1994) and Grossman and Krueger (1995) for example.

[2] For original contributions see Stokey (1998), Andreoni and Levinson (2001), and Lopez (1994). A review of these and other competing explanations appears in Chap. 2 of Copeland and Taylor (2003).

[3] This is for example the exact prediction of both Stokey (1998) and Brock and Taylor (2003).

[4] Stokey (1998), Aghion and Howitt (1998) and others adopt an abatement function relating emissions per unit final output, E/Y, to the share of productive factors used in abatement θ, as follows: $E/Y = (1-\theta)^{\beta}, \beta > 0$.

Theories relying on strong compositional shifts or increasing returns also have difficulty matching these data. Empirical work has found a changing composition of output plays at most a bit part in the reductions we have observed (Selden et al. 1999; Bruvoll and Medin 2003). And while increasing returns to abatement may be important in some industries and for some processes, a large portion of emissions come from small diffuse sources such as cars, houses and individual consumptive activity. In each of these cases, increasing returns to abatement seems unlikely. Increasing returns also presents strong incentives for mergers and natural monopoly and unless we bound the strength of increasing returns carefully, increasing-returns-to-scale models predict negative pollution emissions at large levels of output.[5]

To us, the pollution data and the related empirical work on the EKC present three puzzles that need to be resolved by any successful theory. The first puzzle is how do we square the ongoing large reductions in emission intensities with the relatively static pollution abatement costs? The second puzzle is the EKC: what is responsible for the humped-shape profile of pollution levels when graphed against time or income per capita? The third puzzle comes from the empirical literature itself. It is now well known that empirical estimates from EKC style regressions can vary greatly with the sample used and estimation procedure. Do these fragile cross-country empirical results imply that the EKC does not exist, or is the problem the use of empirical methods that are subject to wide variance?

In this paper we show that the Green Solow model provides a very simple explanation for all three puzzles. In addition, the model also suggests an alternative empirical methodology tightly tied to theory. We demonstrate that a robust prediction of the Green Solow model is convergence in emissions per capita across countries. This prediction holds when the pollutant in question follows an EKC pattern to eventually diminish, but importantly also holds if growth is unsustainable and no EKC pattern emerges. This convergence prediction can be evaluated in a number of ways, and indeed there already exists a sizeable empirical literature examining convergence in pollution levels.

In a number of prescient papers John List and a series of coauthors have explored the time series properties of several pollutants to examine convergence in pollution levels across both states and countries. In Strazicich and List (2003) the authors examine the convergence properties of CO_2 over a panel of 21 industrial countries from 1960 to 1997. Using both cross-country regressions and time series tests the authors conclude there is significant evidence that CO_2 emissions per capita have converged. Additional work by Lee and List (2004) and Bulte et al. (2007) employ more sophisticated time series tests or examine new data sources. Overall, their results demonstrate that there is considerable evidence of convergence in pollution levels across both countries (for CO_2) and across states (for both SO_2 and NO_x) although convergence may be stronger over the last 30 years.[6]

Footnote 4 continued
Copeland and Taylor (2003, Chap. 2) show this relationship arises from an assumption on joint production of emissions and output plus constant returns to scale in abatement. For emissions to decline while final output Y grows, E/Y must fall and this implies θ must approach 1. That is, the share of the economy's resources dedicated to abatement must rise along the model's balanced growth path and approach one in the limit. The interested reader can verify this by making the translation into Stokey's notation by setting $1 - \theta = z$, and interpreting the gap between Stokey's potential and actual output as the output used in abatement.

[5] The simplest version of Andreoni and Levinson's theory of increasing returns to abatement has the property that pollution becomes negative for some large, but finite level of output. This feature poses problems in dynamic models where output grows exponentially.

[6] Convergence is also apparent in the earlier work of Holtz-Eakin and Selden (1995). These authors examined whether carbon per capita followed an EKC. They found that the carbon EKC turned quite late, if at all, at income per capita levels ranging from 35,000 (1986 U.S. Dollars) to above \$8 million per capita depending on the

In total there is considerable evidence of convergence in measures of pollution emissions. What the Green Solow model offers to this body of work is a theoretical structure that links the strength of convergence to observable variables, makes explicit and testable connections between theory and empirical work, and offers a new method for learning about the growth and environment relationship. Since our empirical methods are tightly tied to theory we can provide evidence based answers to how differences in savings rates and abatement intensities affects emissions growth rates; how differences in population growth rates affect emissions in both the long and short runs; and how convergence in emissions across the developed and developing world is likely to proceed even absent a Kyoto like agreement.

To provide these answers we borrow from techniques used in the macro literature on income convergence to derive a simple linear estimating equation linking growth in emissions per capita over a fixed time period to emissions per capita in an initial period and a limited set of controls. These controls include typical Solow type regressors such as population growth and the savings rate, but also include a measure of pollution abatement costs. Not surprisingly, our empirical methods owe much to previous work in macroeconomics on conditional and absolute convergence; in particular Barro (1991) and Barro and Sala-i-Martin (1991). The Green Solow model also bears a family resemblance to many other contributions in the theory literature given its close connection to Solow (1956). It is similar in purpose to that of Stokey (1998) but differs because Stokey does not consider technological progress in abatement. It is related to the new growth theory model of Bovenberg and Smulders (1995) because these authors allow for "pollution augmenting technological progress", which is, under certain circumstances, equivalent to our technological progress in abatement. It is perhaps most closely related to our own earlier work (Brock and Taylor 2003, 2005) where we tried to match data on pollution abatement costs, the EKC, and emission intensities within a modified AK model with ongoing technological progress in both goods and abatement production. This paper grew out of our earlier attempts to match key features of the pollution and income per capita data within the simplest model possible.

The rest of the paper proceeds as follows. Section 2 presents evidence on pollution emissions and abatement costs for the U.S. and European countries. Section 3 sets up the basic model and develops three propositions concerning its behavior. In Sect. 4 we derive an estimating equation and present an empirical implementation using a panel of CO_2 data from 173 countries. Section 5 concludes.

2 U.S. and European evidence

The starting point for our analysis is three observations drawn from U.S. data: emissions per unit of output have been falling for lengthy periods of time; these reductions predate reductions in the absolute level of emissions; and abatement costs have remained a relatively small share of overall economic activity during the period when emissions fell dramatically. In Fig. 1 we plot US data giving emissions per dollar of (real) GDP over the 1948–1998 period.[7] For ease of reading we have adopted a log scale. We plot emission intensities

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Footnote 6 continued
specification. A key finding was that the marginal propensity to emit (the change in emissions per capita for a given change in income per capita) fell with income levels but that overall emissions were forecast to grow. Recent evidence is contained in Stern (2005, 2007).

[7] Data on U.S. emissions of the criteria pollutants graphed in Figs. 1 and 2 come from the E.P.A. The long series of historical data presented in the figures is taken from the EPA's 1998 report National Pollution Emission Trends, available at http://www.epa.gov/ttn/chief/trends/trends98.pdf. We start at 1948 to eliminate war time

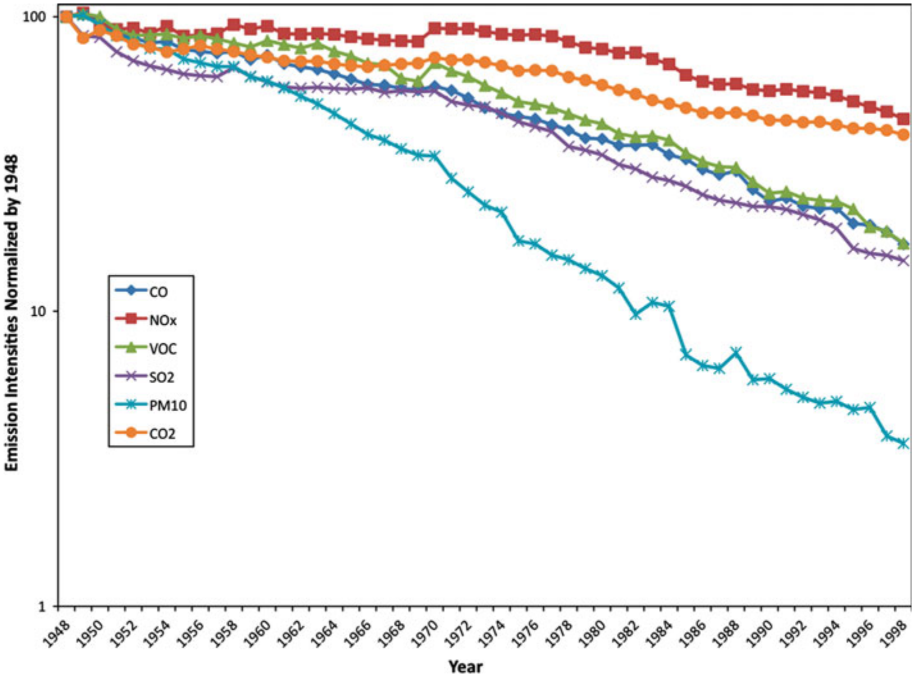

Fig. 1 Emission intensities

for sulfur dioxide, nitrogen dioxide, particulate matter, carbon monoxide, carbon dioxide, and volatile organic compounds. There are two features to note: the first is simply that the emission to output ratio is in decline from the start of the period in 1948; the second, is that (given the log scale for emissions per dollar of output) the percentage rate of decline has been roughly constant over the 50-year period (although it does vary across pollutants).

In Fig. 2 we plot the corresponding emission levels for these same pollutants over the same time period. Figure 2 shows a general tendency for emissions to at first rise and then fall over time. Since US income per capita grew substantially over this period, the time scale in the figure could just as well be replaced by income per capita, and hence it offers a strong confirmation of the EKC as found, for example, by Grossman and Krueger (1994, 1995). The EKC pattern is visible in the data for all pollutants except nitrogen oxides that were approaching a peak, particulates which peaked before the sample period, and carbon dioxide which continued to grow until the 2008 recession.

It is clear however that the reduction in emission intensities shown in Fig. 1 precede the peak level of pollutants in Fig. 2 by 25 years for sulfur dioxide, carbon monoxide, and volatile organic compounds. Particulates have however been falling throughout, but the peak for nitrogen oxides occurs almost 50 years after their emissions per unit output started to decline. Carbon emissions did not peak during the sample period, despite the reduction in the carbon

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Footnote 7 continued
effects and give us a clean 50 year period. Because prior to 1985 fugitive dust sources and other miscellaneous emissions were not included in PM10 we have removed these components to make the data comparable over time. Trends reports subsequent to 1998 do not include these long consistent historical series. As well, the trends report warns that data prior to 1970 reflect a different methodology; hence the kinks at 1970 may be due to this change.

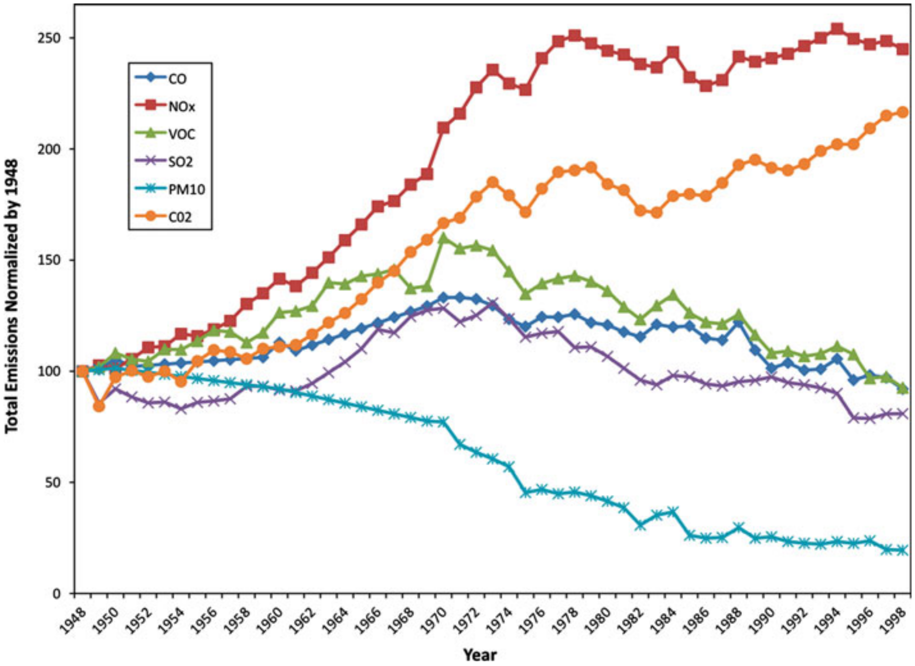

Fig. 2 Total emissions by pollutant and year

intensity of production. If we take the early to mid 1970s as the start of serious pollution regulation, then threshold theories predict an unchanged and therefore horizontal line for the emissions to output ratio until the mid 1970s, and then a steep decline that drives aggregate emissions downward. This is not what Figs. 1 and 2 show for any of the five criteria air pollutants listed.

In Fig. 3 we plot total expenditures (both business and government) on pollution abatement costs per dollar of GDP over the period 1972–1995. These 23 years are the only time period where data is available. As shown, pollution abatement costs as a fraction of GDP rise quite rapidly until 1975 and then remain relatively constant. If we consider pollution abatement costs specifically directed to the criteria air pollutants and scale this by real U.S. output, the ratio is then incredibly small—approximately one half of 1% of GDP—and has remained so for over 20 years (see Vogan 1996).[8]

To demonstrate that these features of the data are not U.S. specific we present the available evidence from European countries in Table 1. The table presents summary statistics for the average yearly percentage change in emissions per unit GDP over the 1980–2001 period; and where possible, the table indicates when aggregate emissions peaked but in many cases this is prior to the start of the sample as indicated by the entry "<1980". In the last column we list the average value of pollution abatement costs as a fraction of GDP for these same countries.

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[8] There is of course considerable controversy over whether these figures represent the full cost of environmental regulation, and they necessarily ignore the significant abatement done prior to the 1970s by cities, utilities, and businesses.For an illuminating historical account of pollution regulation in the US from 1940 to 1970 see Dewey (2000). Dewey details the efforts at pollution control in major US cities such as New York, St. Louis, Pittsburgh and Los Angeles. The analysis shows serious pollution regulation is not a post 1970s phenomena.

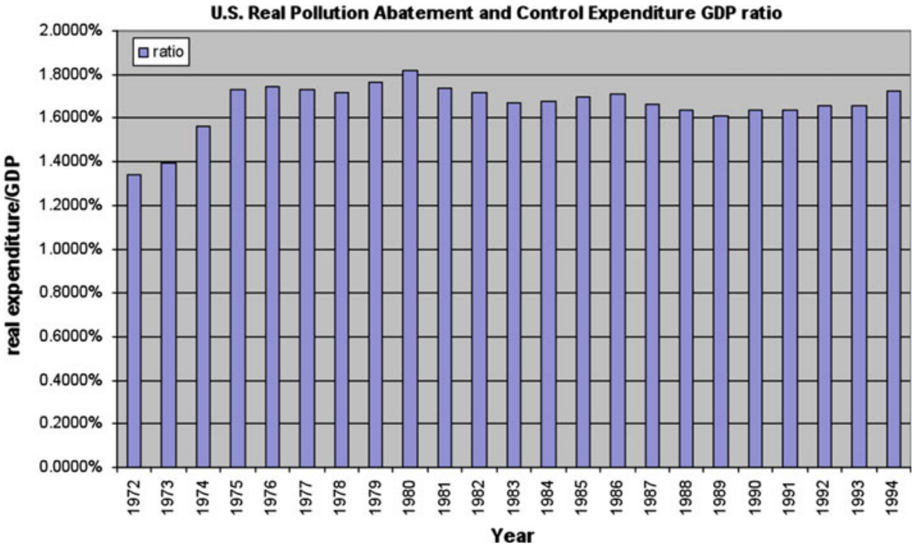

Fig. 3 Pollution abatement expenditures

There are two remarkable features of the data. The first is the massive reduction in emissions per unit of output over the period. Cross country averages are given in the last line of the table. They show reductions are on the order of 4–5% per year for nitrogen oxides, carbon monoxide, and volatile organic compounds but closer to 10% per year for sulfur. The second feature is, of course, the relatively small pollution control costs shown in the last column. On average these costs are only between 1 and 2% of GDP.

The table also gives, where possible, the peak year for emission levels. In many cases these peaks occur before 1980, and with the exception of Portugal and one pollutant for Ireland, the remaining peaks in emissions occurred in the 1980s or early 1990s. Since emissions are now declining for these pollutants and countries, this European data offers strong confirmation that each country pollutant pair exhibits a time profile for emissions consistent with an EKC.[9]

3 The model

We develop an augmented Solow model where exogenous technological progress in both goods production and abatement leads to continual growth with rising environmental quality. We present the simplest specification where both savings and abatement choices are exogenously set. The fixed savings rate assumption is commonly used in the Solow model and is often innocuous. The assumption of a fixed abatement intensity helps us highlight the roles played by diminishing returns and technological progress in generating an EKC. It also allows us to demonstrate how changes in the intensity of abatement—perhaps caused by a dramatic change in environmental policy—affects emission levels and the timing of peak emissions.

Consider the standard one sector Solow model with a fixed savings rate s. Output is produced via a constant returns to scale and strictly concave production function taking effective

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[9] Because, in the words of Andreoni and Levinson, what is now coming down must have first gone up.

Table 1 European evidence

Country	NO_x	Peak	SO_x	Peak	CO	Peak	VOC	Peak	θ Share
Austria	−2.8	<1980	−13.4	<1980	−5.5	<1980	−4.2	1990	1.6
Finland	−3.8	1990	−11.6	<1980	−2.9	<1980	−3.8	1990	1.4
Czech Rep.	−7.6	<1980	−18.6	1985	−4.8	1990	−6.5	1990	2.0
France	−3.8	<1980	−10.0	<1980	−6.4	<1980	−4.2	1985	1.2
Germany	−5.4	<1980	−3.1	<1980	−7.0	<1980	−2.6	1985	1.6
Italy	−2.7	1990	−9.5	<1980	−3.7	1990	−3.8	1995	0.9
Ireland	−2.7	2000	−7.8	<1980	−7.0	1990	−6.3	1990	0.6
Poland	−7.5	1985	−9.9	1985	−10.1	1990	−6.6	<1980	1.6
Slovak Rep.	−4.7	1990	−10.0	<1980	−4.2	1990	−7.5	1985	1.5
Sweden	−4.2	1985	−12.1	<1980	−3.4	1990	−5.1	1985	1.0
Switzerland	−4.4	1985	−9.5	<1980	−6.9	<1980	−5.1	1985	2.1
Netherlands	−4.1	1985	−10.6	<1980	−6.5	<1980	−6.1	<1980	1.7
Hungary	−3.0	<1980	−7.7	<1980	−3.7	<1980	−2.3	1985	0.6
Portugal	1.0	2000	−2.5	1999	−3.4	1995	1.1	1997	0.6
UK	−4.5	<1980	−9.4	<1980	−5.9	<1980	−4.9	1990	1.5
Average	−4.0	–	−9.7	–	−5.4	–	−4.5	–	1.3

Notes Entries under specific pollutant headings represent the average annual percentage reduction in emissions per unit of real GDP over the 1980–2000 period. Dates listed under the heading "Peak" indicate the year when emission levels peaked, with <1980 implying a peak prior to 1980. Table 1 is constructed using three data sources. Data on European pollution emissions comes from the monitoring agency for LRTRAP available at http://www.emep.int/. Real GDP data is taken from the World Bank's Development Indicators 2002 on CD Rom. Entries under θ represent pollution abatement costs as a fraction of national income. They are constructed from the 1996 and 2003 OECD publications "Pollution abatement and control expenditures in OECD countries", Paris: OECD Secretariat. See the Appendix to Brock and Taylor (2004) for details on construction

labor and capital to produce output, Y. Capital accumulates via savings and depreciates at rate δ. The rate of labor augmenting technological progress is given by g_B.

$$Y = F(K, BL), \quad \dot{K} = sY - \delta K \qquad (1)$$
$$\dot{L} = nL, \quad \dot{B} = g_B B$$

where B represents labor augmenting technological progress and n is population growth.

To model the impact of pollution we follow Copeland and Taylor (1994) by assuming every unit of economic activity, F, generates Ω units of pollution as a joint product of output.[10] The amount of pollution released into the atmosphere will differ from the amount produced if there is abatement. We assume abatement is a constant returns to scale activity and write the amount of pollution abated as an increasing and strictly concave function of the total scale of economic activity, F, and the economy's efforts at abatement, F^A. If abatement at level A, removes the ΩA units of pollution from the total created, then we have pollution emitted equals pollution created minus pollution abated, or:

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[10] This approach has been subsequently employed by many authors (Stokey 1998; Aghion and Howitt 1998, etc.). In these other papers, Ω is taken as constant over time and by choice of units set to one. Some authors (for e.g., Stokey 1998) who adopt this approach refer to the firm's or planner's problem as one of choosing across dirty or clean technologies rather than less or more abatement. These approaches are identical.

$$\begin{aligned} E &= \Omega F - \Omega A(F, F^A) \\ E &= \Omega F \left[1 - A(1, F^A/F)\right] \\ E &= \Omega F a(\theta), \end{aligned} \tag{2}$$

$$\text{where } a(\theta) \equiv \left[1 - A(1, F^A/F)\right] \text{ and } \theta = F^A/F$$

where the second line follows from the linear homogeneity of A, and the third by the definition of θ as the fraction of economic activity dedicated to abatement. We assume the intensive abatement function satisfies $a(0) = 1$ and note $a'(\theta) < 0$ and $a''(\theta) > 0$ by concavity. Abatement has a positive but diminishing marginal impact on pollution reduction. In some cases we will adopt the specific form $a(\theta) = (1-\theta)^{\epsilon}$ where $\epsilon > 1$.

To combine our assumptions on pollution and abatement with the Solow model, we note that taking abatement into account, output available for consumption or investment Y, then becomes $Y = [1-\theta]F$. And to match the Solow model's exogenous technological progress in goods production raising effective labor at rate g_B, we assume exogenous technological progress in abatement lowering Ω at rate $g_A > 0$. Transforming our measures of output, capital and pollution into intensive units, we obtain:

$$y = f(k)[1-\theta] \tag{3}$$

$$\overset{\bullet}{k} = sf(k)[1-\theta] - [\delta + n + g_B]k \tag{4}$$

$$e = f(k)\Omega a(\theta) \tag{5}$$

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

3.1 Balanced growth path

Assume the Inada conditions hold for F, then with θ fixed it is immediate that starting from any $k(0) > 0$, the economy converges to a unique k^* as in the Solow model. As the economy approaches its balanced growth path, aggregate output, consumption and capital all grow at rate $g_B + n$ while their corresponding per capita magnitudes grow at rate g_B. Using standard notation for growth in per capita magnitudes, along the balanced growth path we must have $g_y = g_k = g_c = g_B > 0$. A potentially worsening environment however threatens this happy existence. Since k approaches the constant k^* we can infer from (5) that the growth rate of aggregate emissions along the balanced growth path, $g_{E,}$ is given by:

$$g_E = g_B + n - g_A \tag{6}$$

The first two terms in (6) represent the scale effect of growth on emissions since aggregate output grows at rate $g_B + n$ along the balanced growth path. The second term is a technique effect created by technological progress in abatement.

Define sustainable growth as a balanced growth path generating both rising consumption per capita and an improving environment. Sustainable growth is guaranteed by:

$$g_B > 0 \quad \text{and} \quad g_A > g_B + n \tag{7}$$

Technological progress in goods production is necessary to generate per capita income growth. Technological progress in abatement must exceed growth in aggregate output in order for pollution to fall and the environment to improve.

3.2 Diminishing returns and the EKC

The Green Solow model, although simple, generates a very suggestive explanation for much of the empirical evidence relating income levels to environmental quality. Despite the fact that the intensity of abatement is fixed, there are no composition effects in our one good framework, and no political economy or intergenerational conflicts to resolve, the Green Solow model produces a path for income per capita and environmental quality that traces out an EKC.[11] This is not to suggest that the EKC pattern we have seen in the U.S. or European data is necessarily independent of policy choices made in those regions, but rather that a tightening of policy per se is not required for the result.

To demonstrate we use the two panels in Fig. 4. The top panel plots the growth rate of emissions and capital against capital per effective labor and is very similar to graphical representations of the Solow model. The second follows from the first and plots the level of emissions as a function of capital per effective worker and is very similar to representations of the EKC. To start we need to develop a differential equation for emissions. To generate closed form solutions, we adopt a Cobb-Douglas formulation with a constant capital share α, with $0 < \alpha < 1$ as this allows us to write emissions at any time t as:[12]

$$E = B(0)L(0)\Omega(0)a(\theta)\exp[g_E t]k^{\alpha} \tag{8}$$

where $B(0)$, $L(0)$, and $\Omega(0)$ are initial conditions, and use has been made of (2), (6), and the linear homogeneity of F. Differentiate with respect to time to obtain the growth rate of emissions:

$$\frac{\dot{E}}{E} = g_E + \alpha\frac{\dot{k}}{k} \tag{9}$$

where we note the rate of change of capital per effective worker is simply:

$$\frac{\dot{k}}{k} = sk^{\alpha-1}(1-\theta) - (\delta + n + g_B) \tag{10}$$

Using these two expressions we can now link the dynamics of capital accumulation to the evolution of pollution levels using the two panels of Fig. 4.

In the top panel of Fig. 4 we plot on the vertical axis the rates of change of (α times) capital per effective worker $\alpha\dot{k}/k$ and aggregate emissions $\dot{E}/E$, and on the horizontal axis capital per effective worker k. In drawing the figure we have implicitly assumed growth is sustainable: i.e., $g_E < 0$. We refer to the negatively sloped line given by $\alpha sk^{\alpha-1}[1-\theta]$ as the savings locus since it shifts with the savings rate s. The savings locus starts at plus infinity and approaches zero as k grows large; therefore, it must intersect the two horizontal lines as shown by points T and B. From (10) it is clear that the vertical distance between $\alpha sk^{\alpha-1}[1-\theta]$ and the horizontal line with height $\alpha[\delta + n + g_B]$ is just α times the growth rate of capital per effective worker or $\alpha\dot{k}/k$.

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[11] For example, although we take θ as exogenous and independent of other model features, it is likely that tighter regulation spurs technological progress in abatement and hence is related to our primitive g_A. For empirical evidence along these lines see the recent survey by Popp et al. (2009). Xepapadeas (2005) also notes that technological progress in abatement can generate an EKC pattern. His discussion is brief and appears in a review article as does our first discussion of Green Solow in Brock and Taylor (2005).

[12] The constant capital share assumption lets us solve for the evolution of $k(t)$ explicitly, but has no impact on the results in general.

Capital per effective worker is therefore rising at all points to the left of B and falling at all points to the right. As is well known, the intersection at point B gives us the steady state capital per effective worker k^*. Growth is most rapid for small k and falls as k approaches k^*. When the economy enters its balanced growth path, $\overset{\bullet}{k}$ is zero and the economy's aggregate output and capital grow at rate $g_B + n$.

Since g_E is constant, we conclude from (9) that the growth rate of aggregate emissions inherits most of the properties of the growth rate of capital per worker. Using the same methods we employed to determine the growth rate in k, we note that the vertical distance between the savings locus $\alpha s k^{\alpha-1}[1-\theta]$ and the horizontal line with height $\alpha[\delta + n + g_B] - g_E$ equals the percentage rate of change of emissions or $\overset{\bullet}{E}/E$. This implies, the growth rate of emissions is zero at T, positive to the left of T and negative to the right of T. Transforming this information into a prediction for emission levels, it is apparent that point T must represent a turning point in emission levels as shown in the bottom panel of Fig. 4. Emission levels

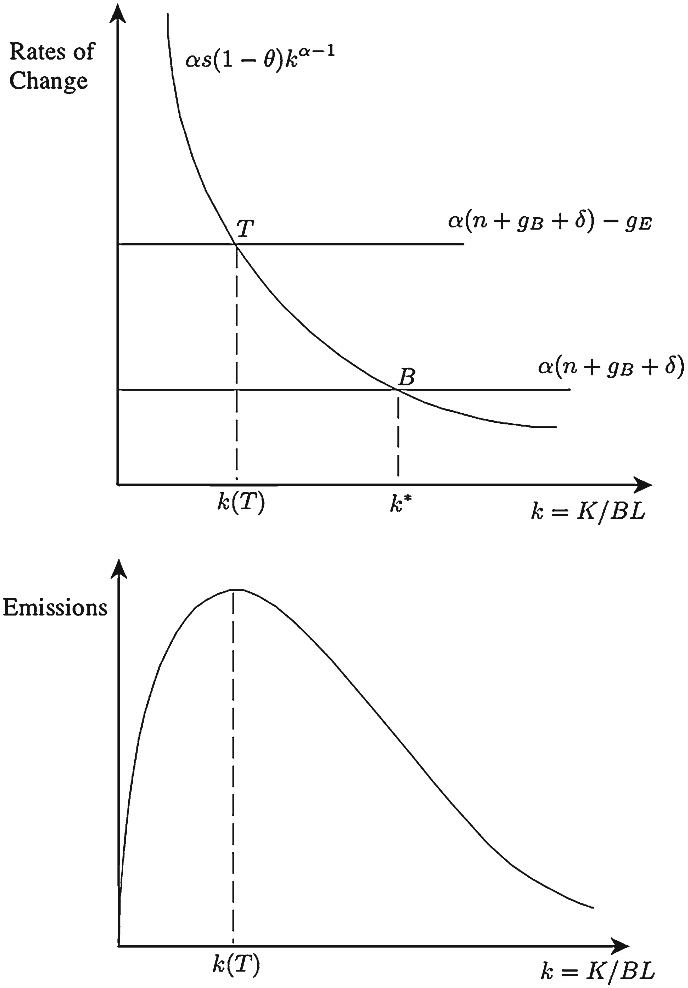

Fig. 4 Total emissions by pollutant and year

are rising to the left of T and falling to the right of T. Under the assumption that growth is sustainable, $g_E < 0$, and point T lies to the left of B: the model generates the EKC profile shown in the lower panel.

The figure illustrates several features of the model. It shows that if growth is sustainable then T lies to the left of B and the time profile for emission levels depends on the location of $k(0)$ relative to point T. If an economy starts with a small initial capital stock then emissions at first rise and then fall as development proceeds: i.e. we obtain a hump-shaped EKC profile for emissions. If initial capital is larger it is possible that the level of emissions falls monotonically as the economy moves towards its sustainable growth path. When emissions peak depends on the relationship between points T and B. For example, if $-g_E$ is small, then T and B differ very little and emissions will only peak as the economy approaches its balanced growth path which may of course take a very long time. When growth is not sustainable T lies to the right of B and emissions will grow forever even as the economy approaches its balanced growth path. In all cases, the economy's intensity of abatement is constant, and its emissions to output ratio falls—both in and out of steady state—at the constant rate $-g_A$.

It is important to note while the model allows for the possibility that emissions may at first rise and then fall, or they may fall continuously or rise continuously, the growth *rate* of emissions is monotonically declining in k. This is true because the growth rate of emissions is very rapid for countries a long way from point B, and slower for those near B. Even in the unsustainable case, the growth *rate* of emissions falls along the transition path until it approaches its balanced growth path rate from above. We will exploit this property later when we derive an estimating equation predicting convergence in emissions across countries. We record these results as a proposition.

Proposition 1 *If growth is sustainable and $k(T) > k(0)$, then the growth rate of aggregate emissions is at first positive but turns negative in finite time. If growth is sustainable and $k(0) > k(T)$, then the growth rate of emissions is negative for all t. If growth is unsustainable, then emissions growth declines with time but remains positive for all t.*

Proof See Appendix

Proposition 1 tells us about the shape of the emissions profile but says very little about the level of emissions and the level of income per capita at the turning point T. Although the model is simple, it can be deceptive in this regard. For example, it is a short step from knowing that $k(T)$ is unique to a belief that income per capita at the turning point is also unique. Similarly, it is easy to assume that the peak emissions level is the same for countries sharing savings rates, population growth rates, etc. Both of these conjectures are wrong: although $k(T)$ is unique, the associated income per capita and emissions level at $k(T)$ are not. □

Proposition 2 *Economies with identical parameter values but different initial conditions produce different income per capita and emission profiles over time. The peak level of aggregate emissions and the level of income per capita associated with peak emissions are not unique.*

Proof in text below.

Proposition 2 offers a simple explanation for the apparent inconsistency between the observation of an EKC in country level data and the fragility of cross-country empirical results. It is now well known that the shape of the estimated EKC can differ quite widely when researchers vary the time period of analysis, the sample of countries, the pollutant, or even the data source. For example, Harbaugh et al. (2002) reconsider Grossman and Krueger's specification and find little support for an EKC using newer updated data. Stern and Common (2001) employ a larger and different sulfur dioxide dataset and find no EKC. And the literature reviews by both Barbier (1997) and Stern (2004) note that published work differs greatly in the estimated turning points for the EKC, the standard errors on turning points are very large, and the results differ widely across pollutants and countries. Criado (2008) comes to similar conclusions. At the same time, plots of raw pollution data for the US and other countries often present a dramatic confirmation of the EKC.

If EKC profiles for even very similar countries are not unique because of differences in initial conditions, then unobserved heterogeneity is surely a problem. Unobserved heterogeneity could then account for the large standard errors on turning points and the sensitivity of results to the sample. □

3.3 Turning points

To examine the determinants of emissions and income per capita at the peak, we start by writing income per capita at any time t as:

$$y^c(t) = [1-\theta]k(t)^\alpha B(0)\exp[g_B t] \tag{11}$$

which is a function of $k(t)$, time t, the intensity of abatement θ, and the initial condition $B(0)$. Denote by $t = T$, the calendar time at which emissions reach their peak. At $t = T$, the economy's capital per effective worker reaches $k(T)$. To solve for the $k(T)$ identified in Fig. 4, substitute (10) into (9) and set it to zero to find:

$$k(T) = \left[\frac{s(1-\theta)}{n+g_B+\delta-g_E/\alpha}\right]^{1/(1-\alpha)} \tag{12}$$

Next solve the differential equation in (10) to find:

$$k(t) = \left[k^{*(1-\alpha)}(1-\exp[-\lambda t]) + k(0)^{(1-\alpha)}\exp[-\lambda t]\right]^{1/(1-\alpha)} \tag{13}$$

As expected $k(t)$ is an exponentially weighted average of initial capital per worker $k(0)$ and its balanced growth path level k^* where the weight given to initial versus final positions is determined by the speed of adjustment $\lambda = [1-\alpha][n+g_B+\delta]$ and time t. k^* is found by setting (10) to zero to find $k^* = [[s(1-\theta)]/[n+g_B+\delta]]^{1/(1-\alpha)}$. Finally, we now set $k(t)$ equal to $k(T)$ to find an implicit equation for the time it takes to reach the peak level of emissions. T is defined by:

$$T : k(T) = \left[k^{*(1-\alpha)}(1-\exp[-\lambda T]) + k(0)^{(1-\alpha)}\exp[-\lambda T]\right]^{1/(1-\alpha)} \tag{14}$$

where $k(0) = K(0)/B(0)L(0)$. Rearranging (14) we find:

$$T = \frac{1}{\lambda}\log\left[\frac{k^{*(1-\alpha)} - k(0)^{1-\alpha}}{k^{*(1-\alpha)} - k^{T(1-\alpha)}}\right] \tag{15}$$

The calendar time needed to reach peak emissions is declining in the convergence speed of the Solow model, λ, increasing in the gap between initial and final capital per effective worker, and is larger the closer is point T to B. Peak emission levels follow similarly. Putting all this together we can now write income per capita at the peak as:

$$y^c(T) = [1-\theta][k(T)]^\alpha B(0)\exp[g_B T] \tag{16}$$

Income per capita at the peak is rising in capital per effective worker at the peak, and rising in the calendar time T needed to reach the peak.

To find peak emissions we use (13) and (8) to find:

$$\begin{aligned} E(t) &= c_0 \exp[g_E t] \left[\left[k^{*(1-\alpha)}(1-\exp[-\lambda t]) + k(0)^{(1-\alpha)} \exp[-\lambda t] \right]^{\alpha/(1-\alpha)} \right] \\ c_0 &= B(0)L(0)\Omega(0)a(\theta) \end{aligned} \tag{17}$$

and hence peak emissions are just:

$$E(T) = c_0 \exp[g_E T]\, [k(T)]^{\alpha} \tag{18}$$

Peak emissions are rising in the capital intensity of the economy, and when growth is sustainable they are falling in the time to reach peak emissions.

It is now easy see that if we compare two economies with the same parameters—savings rate, population growth rates, rate of depreciation, rates of technological progress, and capital share—and hence the same k^*, these economies will not share the same income per capita level at their peak level of emissions, nor will they share the same peak level of emissions.

The logic is straightforward although lengthy. Peak emissions are reached when the rate at which emissions are created via output growth is exactly offset by the rate at which they are abated. The share of output allocated to abatement as an input is constant over time, but technological progress in abatement is raising the effectiveness of these inputs at the constant rate g_A. The rate at which emissions are created declines monotonically as the economy approaches its balanced growth path; the rate of technological progress in abatement is constant. Therefore, the time T at which these two rates equalize is determined by how far initial capital per effective worker is from its eventual steady state. The further is initial capital from its steady state, the faster is economic growth and the longer it is before the growth in emissions hits zero.

This logic tells us that the time to peak emissions, T, is longer the smaller is $k(0)$, but T itself is independent of any variation in initial conditions that leaves $k(0)$ unchanged. Consequently if we alter initial conditions slightly by raising the effectiveness of labor in period zero, $B(0)$, but make compensating changes in the labor force or initial capital stock to leave $k(0)$ unchanged, then we will have left T unchanged. But carrying this thought experiment forward we know that since labor is more productive to start with, income per capita at the peak level of emissions is now higher than otherwise. An exactly analogous argument can be used to show that peak emissions are not unique. Since $\Omega(0)$ plays no role in determining $k(T)$ or T; variations in it alter the peak level of emissions directly via (8).

Since empirical work relates income per capita to emissions and not time as we have here, it is useful to make the connection between our theory and the existing empirical work precise. To do so we note from (13) and (11) that $y^c(t)$ is a strictly increasing function of time. We can therefore invert it finding $t = \phi(y^c)$ and substitute for time in (17). This gives us a parametric relationship between aggregate emissions and income per capita. Establishing the properties of this relationship requires further work that we leave to the appendix, but we note here:

Proposition 3 *There exists a parametric relationship between aggregate emissions E and income per capita y^c that we refer to as an EKC. If $k^* > k(T) > k(0)$, then emissions first rise and then fall with income per capita. If $k^* > k(0) > k(T)$, then emissions fall monotonically with income per capita.*

Proof See Appendix

3.4 Comparative steady state analysis

Most of the empirical work investigating the EKC employs cross country data that includes both developed and developing countries and often both democratic and communist states. Clearly these economies differ in much more than just initial conditions, and this heterogeneity may further confound estimation. To investigate how differences across countries in savings, abatement and rates of technological progress affect emissions growth, we now conduct a comparative steady state analysis.

Consider the role of savings. A change in the savings rate has no effect on the long run growth rate of emissions or output, but it can have an impact on transitional growth and hence an economy's income pollution path. An increase in the savings rate shifts the savings locus rightward raising both T and B in Fig. 4. Greater savings raises capital per effective worker in steady state and capital per effective worker at the turning point. If we substitute for k^* and $k(T)$ in (15) it is possible to show that an increase in the savings rate lengthens the time to peak emissions, T. Therefore, an economy with a higher savings rate reaches its peak emissions level at a higher income per capita than otherwise. The intuition is simple. The turning point for emissions rises because higher savings implies more rapid capital accumulation. This in turn means faster output growth and faster emissions growth at any given k. The turning point in emissions is reached when diminishing returns to capital accumulation lowers output growth to such an extent that it now equals $-g_A$. A higher savings rate makes this task harder, and hence $k(T)$ and T rises.

An increase in abatement intensity has quite interesting impacts. Given the prominent role policy changes have played in explanations for the EKC, but not in the formulation presented here, it is important to discuss these impacts at some length. It is clear that a change in the intensity of abatement has no long run impact on the economy's growth rate in terms of output or emissions, just as differences in savings rates have no long run impact. To verify this inspect (17). In the long run, the path for aggregate emissions is fully determined by its growth rate, g_E, and its level which is set by initial conditions, k^*, and $a(\theta)$. A permanent change in policy that raises θ, lowers the entire path of emissions by lowering the capital intensity of the economy and hence output at every t, lowering emissions per unit output because the policy requires cleaner techniques, but it does not affect the long run growth rate of emissions.

Within the confines of the Green Solow model, tighter policy that raises θ cannot turn an unsustainable growth path into a sustainable one.[13] But this does not mean that policy has no impact on emissions growth, incomes or turning points. Tighter policy creates a policy induced drag on transitional growth, and this affects everything. To see why note that an increase in abatement lowers $(1-\theta)$ and shifts the savings locus leftward thereby lowering both T and B. Using (15) we find the time to peak emissions T falls. Therefore, a higher abatement intensity implies that peak emissions are reached at a lower level of income per capita than otherwise; the peak in emissions is reached earlier than otherwise, and emission levels are lower. Interestingly, emissions start their decline at a lower income per capita not because abatement is effective in lowering the level of emissions (although it does do this in a level sense), but because abatement uses up scarce resources that would otherwise have gone to investment and spurred growth. A higher intensity of abatement, creates a policy induced drag on the rate of transitional growth and it is this impact that lowers $k(T)$. So, even though a permanent change in abatement intensity has no long run effect on emission growth

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[13] If the increase in costs created by the policy leads to innovation raising g_A , then policy could have long run impacts.

rates, it does affect the time profile for emissions and income. Since the policy change lowers the level of pollution, research studying its impact could correctly find it effective in lowering pollution, while raising firms costs and perhaps bringing forward a peak in emissions overall.[14]

Finally, consider the impact of changes in technological progress. Start with changes in the rate of progress in abatement, g_A. An increase in g_A, shifts the top line in Fig. 4 upwards lowering $k(T)$. This lowers the growth rate of emissions for any k, and likewise lowers the growth rate of emissions in steady state. This change has no effect on the growth rate of output or on k^*. Using (15) we find T is reduced. Putting these results together we find peak emissions are reached at a lower income per capita than otherwise and earlier than otherwise.

Faster technological progress in goods production has less clear cut effects. An increase in g_B shifts the top line in Fig. 4 downward raising T and the bottom line upwards lowering B. The growth rate of aggregate emissions rises at any k, while the growth rate of capital per worker falls at any k. The time to peak emissions could rise or fall, and hence income per capita at the peak may be higher or lower.

A similar result arises from changes in population growth. Population growth lowers steady state capital per worker and this lowers transitional growth in capital per worker at any given k. But population growth raises emissions directly via a scale effect and this raises both emissions growth and the point at which emissions start to fall. Whether this new higher transition point is reached sooner or later in calendar time is indeterminate and hence so too is the associated income per capita.

These results demonstrate that relationship between income and pollution is exceedingly complex in even this the simplest of models. We have in fact identified three qualitatively different sets of determinants. The first set of determinants are initial conditions ($B(0)$ and $\Omega(0)$) that affect the transition paths for emissions and income but have no effect on steady state magnitudes nor long run growth rates. A second set of determinants (s and θ) affect the transition paths for emissions and income and change steady state magnitudes, but have no impact on long run growth rates. The final set of determinants (g_B, n, and g_A) affect the transition paths for emissions and income, change steady state magnitudes, and alter long run growth rates of output and emissions.

4 Empirical methodology

While many authors have been critical of the EKC methodology, very little has been offered as a productive alternative. In this section we present an alternative method to investigate the growth and environment relationship that draws on existing work in macroeconomics.

The Green Solow model contains two empirical predictions regarding convergence in emissions. The first is that a group of countries sharing the same parameter values—savings rates, abatement intensities, rates of technological progress etc.—but differing in initial conditions will exhibit convergence in a measure of their emissions. This is true even though each of these countries would typically exhibit a unique income and pollution profile over time. We will derive an estimating equation below to show that under the assumption of identical parameters values across countries, the model predicts *Absolute Convergence in Emissions per capita* or ACE. The second prediction is that in a world with heterogenous

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[14] For research documenting the impact of the Clean Air Act Amendments on economic activity and pollution concentrations see Becker and Henderson (2000) for ozone, Chay and Greenstone (2005) for particulate matter, and Greenstone (2004) for sulfur dioxide.

countries we will need to condition on the right country characteristics to find what we will refer to as *Conditional Convergence in Emissions per capita* or CCE.

4.1 Estimating equation

We start with Eq. 8 for emissions but rewrite it in terms of emissions per capita $e^c(t) = E(t)/L(t)$, and income per capita, $y^c(t) = F(t)[1-\theta]/L(t)$. Using standard notation, this gives us:

$$e^c(t) = \Omega(t)a(\tilde{\theta})y^c(t) \tag{19}$$

where $a(\tilde{\theta}) = a(\theta)/[1-\theta]$. Differentiating with respect to time yields

$$\frac{\dot{e}^c}{e^c} = -g_A + \frac{\dot{y}^c}{y^c} \tag{20}$$

As shown, growth in emissions per capita is the sum of technological progress in abatement plus growth in income per capita. We transform (20) into our estimating equation in three steps. First approximate the growth rate of income per capita and emissions per capita over a discrete time period of size N by their average log changes and rewrite the equation as:

$$[1/N]\log[e^c_t/e^c_{t-N}] = -g_A + [1/N]\log[y^c_t/y^c_{t-N}] \tag{21}$$

To eliminate income growth, we follow Mankiw et al. (1992) and Barro (1991) and approximate the discrete N period growth rate of income per capita near the model's steady state via a log linearization to obtain:[15]

$$[1/N]\log[y^c_t/y^c_{t-N}] = b - \frac{[1-\exp[-\lambda N]]}{N}\log[y^c_{t-N}] \tag{22}$$

where b is a constant (discussed in more detail below) and $\lambda = [1-\alpha][n+g_B+\delta]$ is the Solow model's speed of convergence towards k^*.

Finally substitute for income growth in (21) using (22) and eliminate initial period income per capita using $y^c_{t-N} = e_{t-N}/\Omega_{t-N}a(\tilde{\theta})$ from Eq. 19.

By making these substitutions we obtain a simple linear equation relating changes in emissions per capita across i countries (over a discrete period of length N) to a constant and initial period emissions per capita. Since individual elements making up the constant term are not identified we have no prediction concerning the sign. The growth rate of emissions per capita should however fall with higher initial period emissions per capita. Ceterus paribus, a lower emissions per capita e^c_{t-N} corresponds to a lower initial capital per effective worker k_{t-N}. This then implies a rapid rate of growth in aggregate emissions E and hence a rapid rate of growth of emissions per capita. We write this short specification as a simple linear regression with error term μ_{it}.

$$[1/N]\log[e^c_{it}/e^c_{it-N}] = \beta_0 + \beta_1\log[e^c_{it-N}] + \mu_{it} \tag{23}$$

Somewhat heroic assumptions are needed to estimate (23) consistently with OLS. For example, if we assume countries share the same steady state y^*, then countries can differ only in their initial, and largely unobservable, technology levels Ω_{t-N} and B_{t-N}. Mankiw et al. (1992) address this concern by assuming the initial goods technology B_{t-N} differs across countries by at most a idiosyncratic error term. This assumption has however come under

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[15] See our discussion paper Brock and Taylor (2004) for a full derivation.

severe criticism on both econometric and theoretical grounds (see especially Durlauf and Quah (1999)). One concern is that unobserved variation in initial technologies $B_{i,t-N}$ across i may be correlated with e^{c}_{it-N}. For example a technologically sophisticated country with a large $B_{i,t-N}$ may have greater emissions per capita by virtue of its greater output per capita.

While unobserved heterogeneity is certainly a possibility, it may pose less of a problem in our context. The reason is simply that a productive goods technology implies a large initial B_{t-N}, while a productive emissions technology implies a small Ω_{t-N}. Therefore, a technologically sophisticated country at $T-N$ may have the same $\Omega_{i,t-N}B_{i,t-N}$ as a technologically backward country at $T-N$ making unobserved heterogeneity in initial technology levels less of a problem. In some circumstances this heuristic argument is exact. Assume initial technology levels are proportional to each country's initial "technological sophistication" at $T-N$. Denote technological sophistication by $\mathrm{S}_{i,t-N}$ then $\Omega_{i,t-N} = \alpha/S_{i,t-N}$ and $B_{i,t-N} = \beta S_{i,t-N}$ for some α and β positive. Under this assumption, the product, $\Omega_{i,t-N}B_{i,t-N} = \alpha\beta$, is independent of i.

We invoke this argument to justify a decomposition of the unobservable country specific products $\Omega_{i,t-N}B_{i,t-N}$ into an overall cross country mean we denote by $\overline{\Omega_{t-N}B_{t-N}}$ plus a country specific deviation.[16] We assume these country specific deviations, plus standard approximation error in generating our linear form, η_{it} are contained in our error term μ_{it} as shown below in our long specification. OLS is consistent if the covariance of μ_{it} and our right hand side variables is zero.

To generate the long specification we need to unbundle the determinants of the steady state. Before doing so, we should be specific about how our empirical method accounts for the three different sets of variables that determine emissions growth. First, as is common to the growth literature, we assume that rates of technological progress are common worldwide.[17] In addition, we condition on population growth rates.[18] Therefore, the set of factors that determines both steady states and the rate of growth along the balanced growth path are accounted for by either assumption or measurement.

Second, the long specification allows us to condition on abatement and savings, although abatement in the case of carbon (over this period of time) is effectively zero. Therefore, the set of factors that affect only steady state magnitudes are controlled for in the regression.

Finally, under our assumption that a country's initial technological sophistication across both abatement and production technologies are related, we have reduced the across-country variation in initial conditions. Therefore, under this assumption, differences in initial conditions are accounted for in the estimation.

To generate our long specification it proves useful to adopt as the specific form of the abatement function $a(\theta) = (1-\theta)^{\epsilon}$ where $\epsilon > 1$. This formulation follows from a constant returns abatement function, and like all iso-elastic functions it is quite useful in empirical work. Then letting s_i, θ_i, and $(n + g_B + \delta)_i$ be the time-averaged country specific savings rate, abatement intensity and effective depreciation rate respectively, and substituting for the determinants of y^* we write the long specification as:

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[16] The interested reader should note that even when countries share parameter values and satisfy this mean technology requirement, their income pollution profiles are still not unique making EKC estimation problematic.

[17] See Stern (2005, 2007) for an approach allowing for country specific rates of technological progress in abatement technology.

[18] We also follow the literature by ignoring the reliance of λ on population growth rates and estimate a linear specification.

$$\begin{aligned}
[1/N]\log[e^c_{it}/e^c_{it-N}] &= \beta_0 + \beta_1 \log[e^c_{it-N}] + \beta_2 \log[s_i] \\
&\quad + \beta_3 \log[1-\theta_i] + \beta_4 \log[(n+g_B+\delta)_i] + \mu_{it}
\end{aligned} \tag{24}$$

$$\beta_0 = g_B - g_A + \frac{[1-\exp[-\lambda N]]}{N}[\log \overline{\Omega_{t-N} B_{t-N}}]$$

$$\beta_1 = -\frac{[1-\exp[-\lambda N]]}{N} < 0,$$

$$\beta_2 = [\alpha/(1-\alpha)]\frac{[1-\exp[-\lambda N]]}{N} > 0$$

$$\beta_3 = [\alpha/(1-\alpha)+\epsilon-1]\frac{[1-\exp[-\lambda N]]}{N} > 0$$

$$\beta_4 = -\beta_2 < 0$$

$$\mu_{it} = \frac{[1-\exp[-\lambda N]]}{N}\log\left[\Omega_{i,t-N}B_{i,t-N}/\overline{\Omega_{t-N}B_{t-N}}\right] + \eta_{it}$$

The short and long specifications differ in two important respects. First, when countries differ in the determinants of their steady states, estimating the short specification forces this unexplained heterogeneity into the error term. If these excluded determinants are correlated with emissions per capita this exclusion generates biased and inconsistent estimates. Therefore, when data is available on the determinants of the steady state, the long specification is preferred. Second, the long specification unbundles the determinants of the steady state. It is then possible to link potential policy changes (affecting either say savings and population growth rates) with their environmental outcomes. This is clearly a large advantage as it provides us with the possibility of evidence-based answers to important policy questions.[19]

4.2 Data

To conduct our empirical work we employ data on carbon dioxide emissions. While carbon is not a typical pollutant in many regards, it offers an especially good environment for us to test the model.[20] There are four reasons for examining carbon.

The first is simply that the Green Solow model places very heavy emphasis on the interrelated roles of capital accumulation and technological progress, and very little emphasis on the role played by changes in environmental policy. Prior to the late 1990s there was no abatement of carbon, and hence this cost share is effectively constant at the value of zero. Therefore, any tendency towards convergence in the carbon data is not likely to be due to

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[19] Another possibility is to eschew cross-sectional analysis completely because of issues of unobserved heterogeneity and adopt a panel data method as in Islam (1995). While this is indeed possible, Durlauf and Quah (1999, pp. 283–287) argue that the panel data approach comes with its own quite severe limitations. See also footnote 25.

[20] The use of carbon requires some rethinking of the model relationships. Pollution is now carbon and comes from energy use; carbon reducing technological progress arises from advances reducing energy per unit GDP. With these redefinitions, the Green Solow model then bears a family resemblance to the DICE model of Nordhaus (2008) which also exhibits an exogenous rate of decline in carbon per unit GDP.

convergence in say environmental policy across countries. In this sense, carbon is an especially clean case to test the forces highlighted by the Green Solow model.

Second, it is virtually impossible to obtain reliable cross-country data on pollution emissions from a broad spectrum of countries over any considerable length of time. The Global Environment Monitoring system offers us reliable data on pollution concentrations worldwide since the mid 1970s, but obtaining similar data on emissions is not possible. This is clearly a problem. Identifying the impact of differences in savings rates and population growth rates on emissions requires significant cross country variation in the data, and any credible test of convergence requires data over long periods of time. Carbon data is available for a broad spectrum of countries over lengthy periods of time.[21]

Third, researchers have had great difficulty making sense of the carbon data. There is much disagreement over whether carbon emissions per capita are converging or diverging worldwide.[22] Understanding the dynamics of carbon is also critical to decisions over the appropriate response to global warming. Many of the computable models used to generate business as usual trajectories assume some degree of convergence across countries; if however emissions per capita do not converge or converge only slowly then existing business-as-usual trajectories may be seriously in error.

Finally, the existing evidence on European and U.S. criteria pollutants shows that pollution emissions are falling across the board for many countries. In contrast, carbon emissions are not trending downward. As a result, carbon offers us the opportunity to disentangle the observation of an EKC like pattern in the data from the less restrictive prediction of convergence. Since convergence in emissions per capita is the key prediction of the Green Solow model it is useful to examine a pollutant that does not appear to follow an EKC pattern.

We collected data on carbon emissions per capita, population growth rates and the investment share of GDP for a group of 173 countries from 1960 to 1998. The period ending date of 1998 was selected to ensure that Kyoto commitments could have little impact on emissions. The period starting date of 1960 and the cross-country coverage was determined solely by data limitations imposed by the Penn. World Tables and the World Development Indicators database.

We consider five samples. Sample A contains the 173 countries with data on emissions per capita during the relevant period. We use this sample to estimate our short specification and investigate ACE. Sample B includes only those countries where we can evaluate CCE; i.e. the set of countries that have data on population growth and the investment share of GDP. This reduces the sample to 165 countries. Sample C eliminates OPEC members; while Sample D, excludes all those with a population size less than one million in 1960. Sample E, adds to these restrictions by eliminating countries that are "not rated" by the Penn. World Tables.[23]

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[21] Data on emissions at the U.S. state level could also satisfy this requirement, but the mobility of labor and capital across states introduces further complications.

[22] For recent published see Dijkgraaf et al. (2005); a very recent review is "Convergence clubs in per-capita CO_2 emissions: who's converging who's diverging" March 2008, Carlos Ordas Criado and Jean Marie Grether, Institute for Research in Economics, Neuchatel Switzerland, mimeo.

[23] A table of summary statistics for all regressors can be found in the Appendix. The exclusion of OPEC and small countries from a sample is common in the empirical growth literature. For OPEC, the reason for exclusion is simply that oil extraction and not value-added activities are responsible for most of GDP. For very small countries, their industrial structure often reflects peculiar features such as a financial or trading entrepot. The exclusion of countries on the basis of data quality is also common.

Table 2 Carbon convergence across the world

Variable	(A)	(B)	(C)	(D)	(E)
Cons	0.021	−0.105	0.005	−0.005	−0.049
	(11.6)	(−2.0)	(0.13)	(−0.12)	(−0.87)
$\log e_t^c$	−0.005	−0.007	−0.008	−0.011	−0.012
	(−5.6)	(−5.8)	(−5.9)	(−6.6)	(−6.7)
$\log s$	–	0.029	0.023	0.035	0.041
	–	(3.4)	(2.5)	(3.9)	(4.3)
$\log(n + g_B + \delta)$	–	0.019	−0.029	−0.045	−0.031
	–	(0.93)	(−1.9)	(−2.4)	(−1.35)
N	173	165	151	118	98
Adj. R^2	0.14	0.29	0.31	0.35	0.42

Notes t-statistics are in parentheses. Column A estimates the short version of our model using Sample A described in the text, while the remaining columns estimate a version of our long specification using Samples B–E. The long version is: $[1/N]\log[e_{it}^c/e_{it-N}^c] = \beta_0+\beta_1\log[e_{it-N}^c]+\beta_2\log[s_i]+\beta_3\log[(n+g_B+\delta)_i]+\mu_{it}$ where the dependent variable is the average growth rate in log emissions per capita over the 1998–1960 period, e_{t-N}^c is emissions per capita in 1960, s is the average investment to GDP ratio over the 1960–1998 period, and $(n + g_B + \delta)$ is average population growth over the period plus 0.05 (and therefore captures only variation in population growth rates across countries)

4.3 Results

We present estimates from our short and long specifications in Table 2.[24] In the column (A), we report estimates for the short specification using Sample A with 173 countries. In column (B) we introduce the savings rate and effective depreciation term. Data limitations reduce the sample to 165 countries. Column (C) eliminates OPEC countries; column (D) further limits the sample to countries with an initial population of greater than one million persons. Column (E) adds a further requirement that the country must not obtain a score of “D” in the PWT system of grading.

The Green Solow model does surprisingly well in explaining the cross country variation in emissions per capita growth rates. The results from the short version reported in column (A) are confirmed in each subsequent column as we add conditioning variables and alter the sample. Perhaps not surprisingly, the explanatory power rises as we move rightward in the table with the specification in column E explaining 42% of the variation. We find a positive and significant role for savings in all columns, while effective depreciation is statistically significant in two of the four specifications. In these cases, its sign is negative as required by theory. In all columns the restriction that $\beta_2 = -\beta_3$ cannot be rejected.

The point estimates are in most cases reasonable and similar to those reported in related empirical work. For example, the implied rate of convergence λ varies from a high of 1.6% in column (E) to a low of 0.5% per year in column (A). Using the estimates of β_1 and β_2 (from any column) we can solve for the implied share of capital in GDP which is uniformly too large at approximately 0.7. These two results: a slow rate of convergence and a “too large”

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[24] Recall for carbon $\theta \approx 0$, therefore β_3 is subsumed in the constant. Following Barro (1991), Durlauf and Johnson (1995) and others we employ heteroscedasticity corrected standard error estimates.

capital share are of course the same as those reported by Barro (1991) from an estimation of the standard Solow model.[25]

All together the negative coefficient on initial emissions per capita, the positive role for savings, and the slow rate of convergence all argue that Solow type forces play a major role in determining the growth rate of carbon emissions.[26]

The coefficient estimates also allow us to ask how the high investment rates and fast population growth rates in many developing countries affect the growth rate of their emissions. For example, consider the results presented in column E. Countries within sample E had an average annual growth rate of emissions per capita of 1.98% per year, an average investment share of 21.3%, and an average population growth rate of 1.54% per year. Consider an increase in the investment share, s, of an "average country" by 10% points to a little over 31%. In the very long run, an increase in the savings rate has no effect on emissions growth or emissions per capita growth. Outside of steady state however a higher savings rate implies faster interim growth to reach a new steady state with higher capital per person. Using the coefficient estimates from column E, this 10% point increase in the savings rate would raise the average country's emissions growth rate by 1.57% per year. This is a significant increase since the average growth rate of emissions per capita over the last 30 years is slightly less than 2% per year.

Alternatively, suppose our average country's population growth doubled from 1.54% to a little over 3%. Again in the very long run, this increase has no effect on emissions per capita growth although it must raise overall emissions growth by 1.54%. Outside of steady state, a faster growing population lowers capital per person, lowers labor productivity, slows interim growth and should slow emissions per capita growth as well. To find the magnitude of this effect, start with our average country at the mean of the sample. Then a doubling of population growth implies a reduction in the growth rate of emissions per capita by 0.65% per year. Emissions per capita growth falls with faster population growth, although this effect is temporary. Growth in overall emissions rises both in the transition period and forever. During the transition, overall emissions rise by 0.89% per year; while rising the full 1.54% in the long run.

Alternatively consider the thought experiment of lowering population growth to zero from its current mean. Emissions per capita growth would rise by 0.83%, and overall emissions growth would only fall by 0.71% per year in the interim. In the very long run, emissions growth would fall by 1.54% but the short run out-of-steady-state impact is small.

The purpose of this exercise and these results was to demonstrate that the forces highlighted by the Green Solow model are significant determinants of emissions growth. In contrast to earlier work documenting a finding of convergence in emissions growth or levels, our approach offers a potential window into the determinants of growth and the roles played by investment, population growth and abatement behavior. Additional empirical work (available upon request) employing a panel estimator, examining σ convergence, and testing for

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[25] If we adopt a panel data approach these results change in the expected direction; i.e. the estimated convergence rate increases and capital's share falls (See Islam 2003 for a discussion of the role of panel estimation, and a review of empirical results). Specifically, using a LSDV estimator we find the convergence rate rises to 9–10%, capital's share falls to approximately 0.4, and for all samples (except B) we cannot reject the restriction $\beta_2 = -\beta_3$. Results available upon request.

[26] Two other pieces of evidence concerning convergence are also relevant. If we divide the 1960–1998 period into two equal halves, and examine the mean growth rate of emissions per capita we find it falls over these periods. Therefore mean growth rates are declining as they should. In addition, if we plot the standard deviation of log emissions per capita we find a strong negative trend. Therefore, the distribution of growth rates across countries is narrowing. Results available upon request.

an overall reduction in the average growth rate of per capita emissions across our sample countries strongly support our β convergence findings. Therefore, our approach seems quite successful in the case of carbon.

It remains however an open empirical question whether these same Green Solow forces were critically important to the declines shown in Figs. 1 and 2 for the criteria pollutants in the U.S. or for the European declines shown in Table 1. While our model is suggestive on this score, several puzzles remain. One puzzle is the source of the decline in emission intensities prior to 1970s. If the Green Solow model is correct in attributing this decline largely to technological progress in abatement, what were the incentives for such progress prior to the creation of the E.P.A. or the introduction of stringent regulations in the mid 1970s? In this regard it is important to recognize that pollution regulation did not start in 1970. The Clean Air Act Amendments of 1970 signalled a significant departure from previous regulatory approaches by introducing a strong role at the federal level, but many U.S. states, and municipalities regulated pollution within their jurisdictions all the way back to the 1920s.[27] To the extent that these efforts had bite, there was an incentive to devise methods to meet them at lower cost prior to the 1970s. In addition, some of the reduction in emissions that occurs today, and some that occurred earlier, reflects profit maximizing behavior by firms. For example, recapturing dust particles, eliminating contaminants in waste water so it can be reused, and reducing material use in general can be cost minimizing. So some incentives for innovation in abatement are present without regulation. Finally, to the extent that emissions are tied to energy use there is already an incentive to economize on energy per unit output. If we put these three motives together, there were incentives for pollution reductions prior to the mid 1970s.

Another potential puzzle has already been resolved. The microeconometric evidence linking E.P.A. regulatory efforts to pollution reductions, cost increases, and reduced plant births are not inconsistent with our approach. Changes brought about by the 1970 or the 1977 Amendments to the Clean Air Act could be represented by a permanent level increase in the required abatement intensity θ and we have already shown these changes are effective in lowering pollution, raising costs and slowing (transitional) growth rates. Whether these regulation induced changes were responsible for modest reductions along an emissions path driven by more macro forces, or whether they were the key to the existence of this path requires further research both empirical and theoretical.[28]

5 Conclusion

This paper presented a simple growth and pollution model to investigate the relationship between economic growth and environmental outcomes. A recent and very influential line of research centered on the empirical finding of an EKC has, for the last 15 years, dominated the way that economists and policymakers think about the growth and environment interaction. Numerous empirical researchers have sought to validate or contradict the original EKC findings by Grossman and Krueger (1994, 1995), while theorists have contributed to

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[27] For an entertaining account of the history of regulation during this time period see the book length treatment of this period in Don’t Breathe the Air: Air Pollution and U.S. Environmental Politics: 1945–1970, by Dewey (2000).

[28] For a recent review of studies linking environmental regulations to innovation see Pizer and Popp (2008) and Popp et al. (2009). For theoretical work on induced innovation see Acemoglu (2002), and more specifically Smulders and de Nooij (2003).

this explosion of research by presenting a myriad of possible explanations for the empirical result.

This paper makes three contributions to this line of enquiry. First and foremost it suggests that the most important empirical regularity found in the environment literature—the EKC—and the most influential model employed in the macro literature—the Solow model—are intimately related. While one hesitates to see "Solow everywhere", we have argued that the forces of diminishing returns and technological progress identified by Solow as fundamental to the growth process, may also be fundamental to the EKC finding.

Because of diminishing returns, development starts with rapid economic growth. Emissions rise with output growth but fall with ongoing technological progress in abatement. Rapid growth at first overwhelms the emission reducing impact of technological progress, and emission levels rise. As countries mature and approach their balanced growth path, economic growth slows and the impact of this slower growth on emissions is now overwhelmed by the impact of technological progress in abatement. Emission levels decline. This interplay of diminishing returns and technological progress—key to the convergence properties of the Solow model—generates a time profile of rising and then falling emission levels as income per capita grows along a path of sustainable growth. A tightening of pollution policy raises costs and lowers the level of pollution, but not its long run rate of growth. Environmental policy has a level and not growth effect in the model.

In support of our argument we marshalled several pieces of evidence. We presented evidence that the U.S. emission to output ratio has fallen for almost 50 years; that this reduction predates the peak of emission levels; and that abatement expenditures while growing since the early 1970s have remained a fairly constant and small fraction of economic activity. These data are in many cases inconsistent with current explanations for the EKC.

Our second contribution was to develop a simple extension of the Solow model where the interplay of diminishing returns to capital formation and technological progress in abatement produced a time profile for emissions, abatement costs, and emissions to output ratios that are in accord with U.S. and European data. We also argued that this model could provide a natural explanation for the sometimes confusing and heterogenous results found in the empirical literature.

Finally we developed an empirical methodology that flowed very naturally from our model. By exploiting known results in the macro literature we developed a simple estimating equation predicting convergence in emissions per capita across countries. The model produces several testable restrictions and offers us a new method to learn about the growth and environment relationship. Our empirical evidence is quite strong, and our coefficient estimates provided evidence-based answers to several important questions concerning the evolution of carbon emissions across countries.

Despite these successes there is still much we do not know. How important is the role of technological progress in abatement? How much of the technological progress that we have taken here as exogenous is induced by tightened government policy—how much is the product of firm level efforts to reduce energy costs? In order for us to understand more about the growth and environment relationship, future research in this area must maintain the tight connection from theory to empirical work we have established here, while moving beyond the simplified world of the Green Solow model.

6 Appendix

Table A1 Summary statistics

Variable	(A)	(B)	(C)	(D)	(E)
$[1/N]\log[e_t^c/e_{t-N}^c]$	0.0238	0.0234	0.0210	0.0174	0.0198
	(0.0274)	(0.0271)	(0.0248)	(0.0250)	(0.0241)
$\log e_t^c$	−0.3278	−0.3244	−0.3226	−0.2441	−0.0072
	(1.8078)	(1.8125)	(1.8288)	(1.8881)	(1.7527)
$\log s$	–	3.0512	3.0471	3.0166	3.0614
		(0.3395)	(0.3373)	(0.3133)	(0.2639)
$\log(n + g_B + \delta)$	–	1.9220	1.9010	1.8975	1.8789
		(0.1729)	(0.1551)	(0.1482)	(0.1496)
N	173	165	151	118	98

Note Standard deviations in parentheses

Proposition 1 *Proof* From (9) and (4) the growth rate of emissions is declining in k. By definition emissions growth is zero at $k(T)$. Therefore, if $k(T) > k(0)$ growth is positive but declines with k; if $k(T) < k(0)$ growth is negative and declines with k. When growth is sustainable $k(T) < k^*$. The solution for $k(t)$ in (13) shows $k(T)$ is reached in finite time from $k(0) < k(T)$. If growth is not sustainable, $k(T) > k^*$. The solution for $k(t)$ shows it converges to k^* as time goes to infinity. This implies $k(T) > k^*$ always, and by definition of $k(T)$ emission growth remains positive.

Proposition 2 Proof in the text.

Proposition 3 *Proof* We note from the text that

$$E(t) = c_0 \exp[g_E t]\left[\left[k^{*(1-\alpha)}(1-\exp[-\lambda t]) + k(0)^{1-\alpha}\exp[-\lambda t]\right]^{\alpha/(1-\alpha)}\right]$$
$$y^c(t) = k(t)^\alpha B(0)[1-\theta]\exp[g_B t]$$

We have already shown that for any $k(0) < k^*$, $k(t)$ is increasing in time. Given the properties of exp we can then conclude that $y^c(t) = [1-\theta]k(t)^\alpha B(0)\exp[gt]$ is strictly increasing in time when the conditions of the proposition are met. This allows us to invert and obtain $t = \varphi(y^c)$ where $\varphi' > 0$. Substitute for time in $E(t)$. Now differentiate this parametric function $E(\varphi(y^c))$ with respect to y^c to obtain $E'(\varphi(y^c))\varphi'(y^c)$. Note that if $k^* > k(T) > k(0)$ then $E'(\varphi(y^c))$ is positive for $t < T$, zero at $t = T$, and negative for $t > T$. $\varphi'(y^c)$ is always strictly positive and hence emissions at first rise and then fall with income per capita. If $k^* > k(0) > k(T)$, then $E'(\varphi(y^c))$ is always negative. This implies $E'(\varphi(y^c))\varphi'(y^c)$ is always negative as required.

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