growth) alter peak emissions and income, transitional growth and growth along a balanced growth path. In short these results demonstrate that the relationship between income and pollution is exceedingly complex. And therefore it should come as no surprise that there are large standard errors on turning points and fragile coefficient estimates.

To our knowledge no empirical work examining the growth and environment relationship has used as controls savings rates, population growth rates, etc. that would be suggested by our analysis. But even with information on deep parameters we have already shown that since the EKC profile is reliant on initial conditions, estimation problems remain. One alternative that presents itself is to focus on model predictions that are tightly linked to parameters: that is focus on the relationship between the growth rate of emissions along the transition path rather than the parametric relationship between the level of emissions and income.

3 An Empirical Implementation

We have demonstrated why current empirical methods may have difficulty in estimating an EKC relationship. The income-emissions profile will differ across countries if they differ in initial conditions or in basic parameters such as savings or population growth rates. Criticism is of course much easier than creation, and 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 on absolute and conditional convergence. Our goal is to develop an explicit link between theory and empirical estimation since this link is largely absent in this literature. A secondary goal is to demonstrate Green Solow's ability to explain cross-country patterns of emissions growth with relatively few variables.

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, we obtain a prediction of *Absolute Convergence in Emissions* or ACE. Under the ACE hypothesis differences in the pattern of cross-country growth of emissions per person, is fully explained by differences in initial emissions per person. This prediction follows from the familiar forces of diminishing returns plus an assumption that countries share the same steady state.

The second prediction is that a disparate group of countries will exhibit both very different pollution and income profiles and will not exhibit ACE. Disparate countries will grow outside of steady state at rates that are functions of both differences in initial conditions and differences in country characteristics. In theory if we condition on the right country characteristics, we could estimate a relationship predicting convergence in emissions per person. Since this convergence prediction is akin to the concept of conditional convergence in the macro literature we refer to it as *Conditional Convergence in Emissions*. Here we focus on the model's predictions for ACE within a sample of OECD countries, but also investigate how our results change when we allow countries to differ in savings rates etc. We do so in order to generate and implement a testable equation that may be of use to other researchers.

We conduct our empirical work with data on carbon dioxide emissions. We focus on carbon dioxide for several reasons. Carbon dioxide data exists for a large group of countries over a significant period of time. The large cross country coverage is important since it allows us to show that, as predicted, ACE does not hold over the entire universe of countries in our sample. This sample includes 139 developed and developing economies and this heterogeneity should lead to the failure of ACE.

As well, researchers have had great difficulty in making sense of the carbon data. Estimates of the turning point for carbon are often very high and variable, and hence carbon is one pollutant that may not follow an EKC. Given these difficulties, carbon offers a good testing ground for our approach.

Finally very little direct abatement of carbon emissions has occurred. Some reductions in carbon emissions have come about as a result of other pollution regulations, but much of the trend in carbon emissions per unit output is related to changes in the energy intensity of economies. But changes in energy use per unit output and emissions per unit energy are thought to be responsible for a majority of the reductions we have seen in the set of regulated pollutants.[12] Therefore while carbon is unlike other pollutants because it is unregulated, it is much like other air pollutants in that it is tightly tied to energy use.

3.1 Estimating Equation

We start with equation 9 for emissions but rewrite it in terms of emissions per person $e^c(t) = E(t)/L(t)$, and income per capita, $y^c(t) = F(t)[1-\theta]/L(t)$. Using standard notation, this gives us:

[12] See for example Selden et al. (1999).

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

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

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

where we have made use of our assumption that the fraction of overall resources dedicated to abatement is constant over time. As shown, growth in emissions per person is the sum of technological progress in abatement plus growth in income per capita. Along the balanced growth path this is equal to $-g_A + g$ which may be positive, negative, or zero; outside of the balanced growth path we will approximate the growth rate.

We make equation 20 operational in three steps. First approximate the growth rate of income per capita and emissions per person over a discrete time period of size N by their average log changes and rewrite the equation as:

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

Second use the now standard procedures employed by Mankiw, Romer and Weil (1992) and Barro (1991) to approximate the discrete N period growth rate of income per capita near the model's steady state via a log linearization to obtain:[13]

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

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

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

By making these substitutions we obtain a simple linear equation suitable for cross-country empirical work. It relates log changes in emissions per person across i countries (over a discrete period of length N) to a constant and initial period emissions per person. We write this as a simple linear regression with error term μ_{it}:

[13] See the appendix for a full derivation.

$$
\begin{aligned}
[1/N]\log[e^c_{it}/e^c_{it-N}] &= \beta_0 + \beta_1 \log[e^c_{it-N}] + \mu_{it} \qquad (23) \\
\beta_0 &= g - g_A + \frac{[1-\exp[-\lambda N]}{N}\log[y^* \tilde{a}(\theta)\,\overline{\Omega_{t-N} B_{t-N}}\,] \\
\beta_1 &= -\frac{[1-\exp[-\lambda N]}{N} < 0 \\
\mu_{it} &= \frac{[1-\exp[-\lambda N]}{N}\log\left[\Omega_{i,t-N}B_{i,t-N} - \overline{\Omega_{t-N} B_{t-N}}\,\right]
\end{aligned}
$$

We refer to the specification in 23 as the short specification. 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 only differ in their initial technology levels Ω_{t-N} and B_{t-N}. While Mankiw, Romer and Weil (1992) assume the initial goods technology B_{t-N} differs across countries by at most a idiosyncratic error term, this assumption has come under severe criticism on both econometric and theoretical grounds (see especially Durlauf and Quah (1999)). The primary econometric concern is that unobserved variation in initial technology in $B_{i,t-N}$ across i may be correlated with other right hand side variables determining y^*.

While unobserved heterogeneity is certainly a possibility here as well, 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.[14] We invoke this argument to justify our 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. These country specific deviations plus standard approximation error in generating our linear form are contained in our error term μ_{it} as shown above. OLS is consistent if the covariance of μ_{it} and our right hand side variables is zero.

Since individual elements making up the constant term in 23 are not identified we have

[14] In some circumstances this heuristic argument is exact. For example assume the initial technology levels were proportional to each country's initial "technological sophistication" at $T-N$. Denote technological sophistication by $S_{i,t-N}$ and assume that initial productivity is proportional to technological sophistication; that is, $\Omega_{i,t-N} = a/S_{i,t-N}$ and $B_{i,t-N} = bS_{i,t-N}$ for some a and b positive. Note the product $\Omega_{i,t-N}B_{i,t-N}$ $= ab$ which is now independent of i.

no prediction concerning the sign. The growth rate of emissions per person should however fall with higher initial period emissions per person and this is reflected in the prediction of $\beta_1 < 0$ The intuition for this is simple. Holding the technology levels and abatement intensity fixed, a lower emissions per person 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 person. It is also useful to note that since N is given, any estimate of β_1 carries with it an implicit estimate of the rate of convergence of the Solow model, λ. Since N is fixed, we can back out these estimates of λ and check them against those provided by the cross-country growth literature.

While the short specification is simple it is also unsatisfactory. It is unsatisfactory because the Green Solow's key predictions on emissions follow from the new element g_A and the reliance of y^* and $a(\theta)$ on abatement. Thus far we have assumed g_A and θ are both constant over time and exhibit no cross country variation. But data on these variables are available. Cross country data on the share of pollution abatement costs in GDP shows θ varies little over time, but exhibits substantial cross country variation. Moreover if we take our model literally then g_A equals the rate at which carbon emissions to output falls over time. This ratio is both observable and does vary across countries.

To carry forward these new elements into empirical work we now construct the long specification of our estimating equation. To do so it proves useful to assume $a(\theta) = (1-\theta)^\epsilon$ where $\epsilon > 1$. This formulation follows from a constant returns abatement function, and like all isoelastic functions it is quite useful in empirical work. To generate our long specification we return to our short specification in 23. Let savings, abatement, g_A, and the effective depreciation rate $(n + g + \delta)$ vary across countries by taking on an i subscript, and then substitute for the determinants of y^* to write the long specification as:

$$
\begin{aligned}
[1/N]\log[e^c_{it}/e^c_{it-N}] &= \beta_0 + \beta_1 \log[e^c_{it-N}] + \beta_2[g_{Ai}] \qquad (24)\\
&+\beta_3 \log[s_i] + \beta_4 \log[1-\theta]_i \\
&+\beta_5 \log[(n+g+\delta)]_i + \mu_{it} \\
\beta_0 &= g + \frac{[1-\exp[-\lambda N]]}{N}[\log \overline{\Omega_{t-N} B_{t-N}}] \\
\beta_1 &= -\frac{[1-\exp[-\lambda N]]}{N} < 0, \\
\beta_2 &= -1 < 0 \\
\beta_3 &= [\alpha/(1-\alpha)]\frac{[1-\exp[-\lambda N]]}{N} > 0 \\
\beta_4 &= [\alpha/(1-\alpha) + \epsilon - 1]\frac{[1-\exp[-\lambda N]]}{N} > 0 \\
\beta_5 &= -\beta_3 < 0
\end{aligned}
$$

where g_{Ai} is a country specific estimate of technological progress in abatement (see below), while s_i, $[1-\theta]_i$ and $[(n+g+\delta)]_i$ are the time-averaged country specific savings rate, abatement, and effective depreciation rate respectively. Savings and depreciation are familiar from growth regressions as are several of the restrictions theory imposes on coefficient magnitudes. The long specification does however add new parameters to estimate and provides two new testable restrictions.

Given our earlier discussions it should be apparent that an increase in savings raises the growth rate of emissions per person by raising the steady state capital stock. This positive transitional effect of savings on emissions growth is captured by $\beta_3 > 0$. Since a reduction in abatement raises the economy's steady state capital intensity and raises emissions via reduced abatement, we also have $\beta_4 > 0$. The coefficient sign of β_5 follows directly from the role "effective depreciation" plays in determining a country's steady state capital intensity.

Apart from the usual parameter restrictions contained in the Solow model ($\beta_5 + \beta_3 = 0$, and α should be close to capital's share) the Green Solow model contains the additional restriction of a unitary coefficient on g_A and $\beta_4 - \beta_3 > 0$. Moreover, by judicious use of estimates for β_1, β_3 and β_4 an estimate for ϵ can be constructed. Again, since N is known, we can recover an estimate of λ as well.

There are however new econometric and data complications introduced by the long specification. One concern is a common one. We do not have data for either g or δ, and hence we have to construct our regressor $(n + g + \delta)$ using alternative means. Here we follow the literature in assuming $g + \delta = .05$, and then use observed population growth rates for n to construct the regressor. A second complication arises because strictly speaking once we admit population differences across countries, we should also admit differences across countries in the parameter λ as well. Since doing so would exhaust our degrees of freedom we again follow the literature in treating λ as constant across countries. Since this is somewhat unsatisfactory we will investigate how the inclusion of effective depreciation affects our results.

Finally since technological progress in abatement is a key part of our theory we construct a measure of $g_{i,A}$. This is somewhat problematic since our theory takes $g_{i,A}$ to be exogenous and hence is uninformative on its determinants.[15] But since we are taking the intensity of abatement as fixed over time, we could in theory obtain estimates for $g_{i,A}$ by regressing $\ln(E_{it}/Y_{it})$ on a constant and a time trend. This specification follows directly from our theory's prediction for E/Y as given for example in 9. It seems likely however that although technological progress may be the largest force affecting the time profile for E_{it}/Y_{it}, it is not the only force. Compositional changes, regulations, oil price shocks etc. may all play a role as well. Of these energy prices is probably the most important for our carbon data, and since we do not wish to attribute to technological change what is a compositional change caused by rising energy prices, we allow for energy prices to affect the carbon intensity of production. For each country, i, we obtain our estimates of $g_{i,A}$ by estimating the following (country by country) using OLS:

[15] One generalization that may be worth pursuing is to assume that final output is produced by a continuum of inputs each with a different pollution intensity. In this case we can then write an economy's overall emission intensity as: $E/Y = \int \Omega(z,t)a(z,\theta)\frac{p(z)y(z)}{Y}dz$ where the integral is defined over the set of available inputs; $\Omega(z,t)a(z,\theta)$ is emission per dollar of final output in sector z, and $p(z)y(z)$ is total dollar value added in this sector. Let industry shares be given by $b(z,t) = p(z)y(z)/Y$, with $\int b(z,t)dz = 1$. Then straightforward differentiation will show that even if the rate of technological progress in abatement is identical across sectors (i.e. assume $\Omega(z,t)$ is independent of z), then the rate of change in E/Y will differ from g_A if there are compositional changes in the economy. This suggests that our crude method for estimating g_A could be improved by employing information on sectoral shares and carbon intensity. We intend to investigate this possibility in the future.

$$\log(E/Y)_{it} = \gamma_{i0} + \gamma_{i1} \log p^w_{oil,t} + \gamma_{i2} time + \epsilon_{it} \tag{25}$$

where γ_{i0} is equal to $\log[\tilde{\Omega}_{iT-N} a(\theta_{iT-N})]$, $g_{i,A}$ is given by $-\hat{\gamma}_{i2}$, and t runs from 1960-1998. $p^w_{oil,t}$ is the real US dollar world price for oil, and $(E/Y)_{it}$ is emissions per dollar of real gdp also measured in US dollars. While more sophisticated models for $g_{i,A}$ may improve our estimates, our goal here is to provide preliminary evidence while staying as close as possible to the direct implications of our theory.

3.2 Data

Obtaining good cross country data on pollution emissions is difficult. We used the World Bank's Development Indicator's 2002 for data on carbon emissions per capita, carbon per dollar of GDP, population size, and investment rates. The data starts in 1960 and we take 1998 as our terminal year. Our focus is the OECD sample comprised of 22 countries for which we have a relatively complete set of data from 1960 to 1998. The countries are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, and the United States.[16] We follow the common practice of employing time average values for savings, population growth rates and abatement intensities. Savings is proxied by the average investment to GDP ratio over the 1960-1998 period. Population size is measured using actual population figures (using the working age population has little effect on our results). Data on the share of abatement in GDP is especially spotty. The OECD publishes data on the share of pollution abatement costs in GDP for many OECD countries, but the country coverage is not complete. In theory these data include both public and private sector expenditures, and span the years 1985 to 1998, but few countries have complete coverage.[17] Accordingly we employ averages over the longest period possible and employ the widest measure for pollution abatement cost available (public plus private expenditures when available). For some countries the time averaged estimates reflects relatively few observations. In order not to lose degrees of freedom we calculated the share for Luxembourg directly from OECD sources, and assumed New Zealand had the same abatement intensity as its neighbor Australia. Given the quality of this data the reader is cautioned from drawing strong conclusions from our results.

[16] Germany was excluded because of extensive border changes.

[17] This data is available from the OECD publication "Pollution abatement and control expenditures in OECD Countries", Paris: OECD Secretariat. We present our pollution abatement cost data in the appendix.

3.3 Results

We start by examining the possibility of absolute convergence in emissions. It would of course be surprising to find ACE supported across anything but the most homogenous of country groupings. We expect ACE to fail miserably because any broad set of countries will differ greatly in their rates of savings, population growth and technological progress.

As a starting point for our analysis we present in Figure 7 the yearly average log changes in emissions per person against the log of initial levels for 139 countries available in the World Bank development indicators.[18] As the plot shows there is little apparent relationship between the two series.

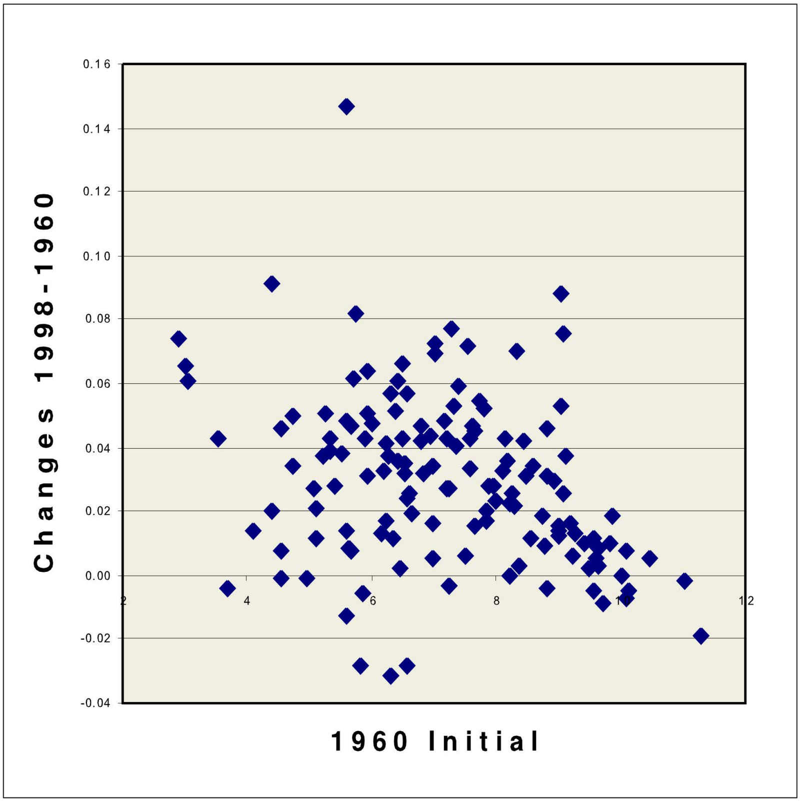

Figure 7: World CO2 Convergence

In Figure 8 we construct the same plot for the sample of OECD countries that we expect are similar in parameter values. The difference is striking. There is obviously a strong negative

[18] This plot includes all countries in the database for which there is data in 1960. Emissions are measured in lbs of emissions per capita for ease of reading.

and very tight relationship between the growth of emissions per person over the 1960-1998 period and 1960 emissions per capita. This is true even though the figure does not correct for any of the differences across countries allowed for in our long specification. The figure shows countries with small emissions per person experienced rapid emissions growth while those with large emissions per person grew far more slowly.

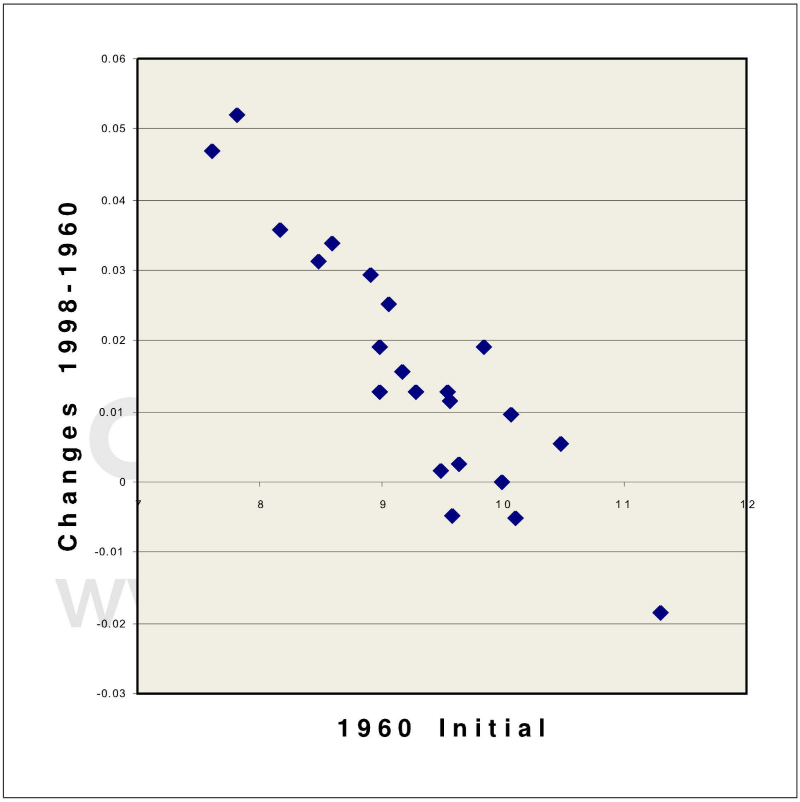

Figure 8: OECD Convergence

To go further we present estimates of our short and long specifications in Table 1.[19] In the first column we report estimates for the short specification. Not surprisingly, initial emissions per person has a negative effect on growth as shown in Figure 8. What is surprising is the goodness of fit, with over 80% of the variation in emissions per person being explained by initial emissions per person alone. This is far above the typical explanatory power of unconditional Solow type regressions.

[19]Following Barro (1991), Durlauf and Johnson (1995) and others we employ heteroscedasticity corrected standard error estimates.

Table 1: Convergence Across the OECD

Variables	(1)	(2)	(3)	(4)	(5)
cons	.045	.041	.005	-.025	.014
	(18.5)	(14.6)	(.11)	(-.58)	(.25)
$\log e^c_{t-N}$	-.018	-.011	-.010	-.010	-.009
	(-11.9)	(-4.1)	(-3.5)	(-3.4)	(-2.5)
$-g_A$	..	-.49	-.49	-.49	-.54
		(-2.7)	(-2.8)	(-2.7)	(-2.8)
$\log s$			.010	.011	.015
			(.75)	(.79)	(.93)
$\log[1-\theta]$				.30	.33
				(.98)	(1.1)
$\log(n+g+\delta)$					-.012
					(-.47)
No. obs	22	22	22	22	22
Adj. R^2	.82	.88	.88	.88	.87

Notes: t-statistics are in parentheses. Each column estimates a version of our long specification under various restrictions.

$[1/N]\log[e^c_{it}/e^c_{it-N}] = \beta_0 + \beta_1 \log[e^c_{it-N}] + \beta_2[g_{Ai}] +$
$\beta_3 \log[s_i] + \beta_4 \log[1-\theta]_i + \beta_5 \log[(n+g+\delta)]_i + \mu_{it}.$

The dependent variable is the average growth rate of emissions per capita over the 1998-1960 period. e^c_{t-N} is emissions per capita in 1960, $-g_A$ is the country specific estimate for the rate of technological progress in abatement, s is the average investment to GDP ratio over the 1960-1998 period, $[1-\theta]$ is one minus the ratio of pollution abatement costs to GDP also averaged over the period, and $(n+g+\delta)$ is average population growth over the period plus .05.

In column (2) we add our measure of technological progress in abatement. This variable enters significantly and with the expected negative sign, although its coefficient estimate is far from the -1 value predicted by theory. Given the method by which we constructed this regressor it is tempting to attribute this to attenuation bias. In column (3) we add the savings rate which enters positively as predicted by theory, but is not significant at conventional levels. In column (4) we add pollution abatement costs. The measure of pollution abatement costs enters positively as predicted by theory, and its magnitude is above that of savings also as predicted by theory. Our measure of abatement costs is however not statistically indistinguishable from zero. Finally for completeness in column (5) we add the final Solow regressor - effective depreciation. This regressor enters negatively as predicted, but likewise enters insignificantly. We can reject a joint F-test that our four added variables are jointly zero ($F(4,16) = 2.82$) at the 6% level, or reject that our two new Green Solow variables (g_A, or θ) are jointly zero ($F(2,16)=4.7$) at the 5% level.

Overall the results from Table 1 are encouraging. Even the simple specification explains over 80% of the variation in carbon per capita growth rates over 1960-1998. While the addition of technological progress in abatement adds something to the model's explanatory power, the remaining regressors lower the adjusted R^2. While the significance level of several key regressors is low, this may be due to the small sample size and poor data quality. Despite the lack of significance for several regressors, point estimates are in most cases reasonable and in line with those reported in related empirical work. For example, the implied rate of convergence λ varies from a high of 1.4% in column (1) to a low of .8% per year in column (5). And using our final regression in column (5) we find the implied share of capital in GDP is approximately .6. These two results, a slow rate of convergence and a too large capital share are of course the same as those reported by Barro (1991) from an estimation of the standard Solow model. Moreover, if we use the estimates from column (5) on savings, abatement and initial emissions per person, we can develop an estimate for ϵ in the abatement technology. In theory ϵ must exceed one. Its point estimate is approximately 35.

Underlying the estimates in Table 1 are of course our estimates of $g_{i,A}$, which we report in Table 2 together with their 95% confidence intervals.

Table 2: Technical Progress Estimates

Country	$-g_{i,A}$	95% C.I.
Australia	-.41	(-0.52, -0.31)
Austria	-1.66	(-1.89, -1.43)
Belguim	-2.95	(-3.21, -2.70)
Canada	-1.39	(-1.59, -1.18)
Denmark	-1.19	(-1.58, -.81)
Finland	-.23	(-.88, .41)
France	-3.01	(-3.34, -2.68)
Greece	2.23	(2.02, 2.47)
Iceland	-2.19	(-2.45, -1.93)
Ireland	-1.31	(-1.60, -1.03)
Italy	-.48	(-.90, -.07)
Japan	-1.35	(-1.67, -1.03)
Luxembourg	-4.72	(-5.10, -4.33)
Netherlands	-1.31	(-1.54, -1.08)
New Zealand	.57	(.36, .79)
Norway	-1.33	(-2.05, -.61)
Portugal	.88	(.64, 1.12)
Spain	-.04	(-.41, .32)
Sweden	-3.03	(-3.57, -2.50)
Switzerland	-.65	(-.97, -.33)
United Kingdom	-2.59	(-2.68, -2.49)
United States	-1.71	(-1.90, -1.52)

Note: t-statistics are in parentheses. For each country we estimate $\log(E/Y)_{it} = \gamma_{i0} + \gamma_{i1}\log p^{w}_{oil,t} + \gamma_{i2} time + \epsilon_{it}$ over the 1960-1998 period. The dependent variable is the log of emissions to GDP measured in US dollars. The estimates for $-g_{i,A}$ above, are the coefficients $\hat{\gamma}_{i2}$.

There are three features of the estimates worth noting. First, most but not all of the estimates are negative. The estimates for Greece, Portugal and New Zealand are positive and significantly so. And we cannot rule out a zero rate of technological progress in either Finland or Spain. Taking our model literally a positive estimate implies technological regress. A more reasonable interpretation is that factors other than oil prices and technological progress are driving the emissions to output ratio in some of these economies. Second, the estimates are quite precise which makes concerns over measurement error in our proxy for technological progress less of an issue. Third, if we ignore outliers, the estimates indicate a rate for g_A of perhaps 1.5 to 2% per year. If we couple this average estimate with average population growth of say 1% per year and per capita income growth of 2%, it is apparent that carbon emissions should not exhibit an EKC pattern. In terms of our theory, point T is to the right of point B.

With these empirical results in hand return to Figure 8. One explanation of the tight relationship shown in Figure 8 is that convergence in the Solow model is generating the result, although this would only literally be true if emissions per unit of output were constant over time. Our results in Table 2 suggest otherwise, but clearly the convergence properties of the Solow model are helping. A further contributing factor may be that unobserved cross country heterogeneity is playing less of a role here than it does in the typical Solow framework. Since a country with a unusually productive goods technology may also be one with an unusually productive abatement technology, unmeasured technological differences may to some extent be netting out in the wash. Finally, there is some evidence in Table 2 of a weak relationship between a country's development level and its estimated g_A. The three countries with positively estimated coefficients had low incomes in 1960. The positive estimates for these countries could reflect a strong compositional shift towards energy and hence carbon intensive manufactures at the earliest stage of development. If this is true, then countries with low incomes and little carbon per person will see emissions rise from both rapid growth via Solow, and a compositional shift towards heavy industry. Countries with high incomes and relatively high emissions per person will see lower growth and a shift away from heavy industry. As a consequence, the convergence predictions of the model may be reinforced by compositional shifts along the development path. Alternatively, relatively poor countries in 1960 may also be relatively slow at assimilating and implementing new abatement technologies. Under this scenario, low income countries countries would see a large increase in carbon per capita because of relatively fast growth but relatively slow progress in adopting new abatement technologies. Together these four reasons - output convergence, compositional shifts, reduced heterogeneity and technology catch up- may explain the strength of our goodness of fit statistics and the tightness of the relationship depicted in

Figure 8.

Although the evidence for convergence in Figure 8 seems undeniable, it is well known that cross-sectional tests such as ours may indicate convergence while time series tests find no such evidence (See for eg. Bernard and Durlauf 1995). Fortunately, in a series of prescient papers John List and a series of coauthors[20] have explored the time series properties of several pollutants to examine convergence in pollution levels across both states and countries. In Stracizich and List (2003) the authors examine the convergence properties of CO2 over a panel of 21 industrial countries from 1960-1997. When the authors estimate a relationship equivalent to our short regression they find evidence very similar to our OECD regression in column (1). The authors then add a series of conditioning variables (temperature, energy prices, and the level and square of per capita income and population density) to allow for conditional convergence but have little success. This is perhaps not surprising in light of our theory since these are not variables determining steady states in the Green Solow model. Stacizich and List supplement their cross-country regressions with a time series test of convergence using a panel unit root test. This time-series test also strongly supports convergence. The authors conclude there is significant evidence that CO2 emissions per capita have converged. Further work by Lee and List (2002) and Bulte et al. (2003) employ newer 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 CO2) and across states (for both SO2 and NOx) although convergence may be stronger over the last 30 years.

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 US Dollars) to above $8 million per capita depending on the specification. A key finding was that the marginal propensity to emit (the change in emissions per person for a given change in income per capita) fell with income levels but that overall emissions were forecast to grow. These findings are consistent with the Green Solow model when $g_A < n + g$. Under these

[20] See List (1999), Lee and List (2002), Strazicich and List (2003), and Bulte, Strazicich and List (2003). This work is largely empirical arguing for a convergence specification by analogy with the Solow model. Bulte et al. (2003) contains theory that extends the Andreoni and Levinson (2001) model to a dynamic environment to derive a testable equation. The resulting derivation is however problematic. Equation (5) of Bulte et al (2003), which gives the balanced growth path level of pollution, produces negative pollution for finite t (when there are increasing returns to abatement which is their standard case and necessary to produce the EKC in the model). Pollution goes to negative infinity as time progresses. When there are constant returns to abatement the EKC is no longer a prediction and their equation (5) yields negative pollution levels for all t when $\alpha > \beta$. These problems seem to have arisen from mapping the strong increasing returns to abatement in the Andreoni and Levinson (2001) model into a model where investment in abatement rises lockstep with aggregate output.

circumstances, convergence in emissions per person still obtains, but emissions still grow along the balanced growth path.

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.

4 Discussion and Extensions

We have presented a very simple theory linking growth rates, income levels and environmental quality. In doing so we have made a host of simplifying assumptions some of which may appear quite limiting. In this section we discuss these assumptions, provide further empirical evidence supporting our approach and develop methods for extending our results.

4.1 Sample Selection, Galton's Fallacy and σ Convergence

Our empirical methods are closely related to those employed in the cross-country growth literature where variation in cross-country growth rates over some period of time are explained by initial income plus other controls. The cross-country growth literature is voluminous and controversial. It started with the work of Baumol (1986), was formalized and extended by the important contributions of Barro (1991) and Barro and Sala-i-Martin (1992), and it played an lead role in Mankiw, Romer and Weil (1992). Durlauf and Quah (1999) provide an excellent critical review of the empirical literature.

Since our methods are similar, some - but not all - of the criticisms of cross-country growth regressions are relevant to the estimates we provided here. The earliest critique came from DeLong (1988) who argued that Baumol's (1986) original finding of convergence in productivity levels across 16 currently rich countries was the result of sample selection and measurement error. Measurement error was a potentially important econometric problem since the data spanned the 1870 -1979 period, with the quality of the 1870 data quite uncertain. As DeLong noted measurement error in the estimates of 1870 values worked towards the convergence finding. Since our data only spans the 1960-1998 period we think the measurement error issues discussed by DeLong are largely irrelevant here.

Sample selection may however be an issue, and DeLong argued that the 16 countries chosen by Baumol were ex post winners who undoubtedly differed in their productivity levels in earlier years; as a consequence the convergence finding was all but guaranteed.

Sample selection could be an issue with our dataset. For example, the convergence we find and attribute to the interplay of diminishing returns and technological progress, could arise from convergence in environmental policies driven by income convergence across the rich OECD countries in our sample. While this is a possibility two pieces of evidence work in our favor. The first is that carbon emissions are largely unregulated and have been largely unregulated for many years. Therefore convergence in carbon emissions is unlikely to arise from forces causing convergence in environmental policies amongst the OECD.[21]

The second piece of evidence is shown in Figure 9 below. Here we follow DeLong's advice and extend our sample of rich OECD countries to include all other countries that as of 1960 were at least as well off as the poorest OECD member included (Portugal). Extending the sample in this way gives us a sample of 32 countries; ten of which do not appear in the high income OECD in 1998.[22] As shown by Figure 9, the strong convergence properties remain with the larger sample.

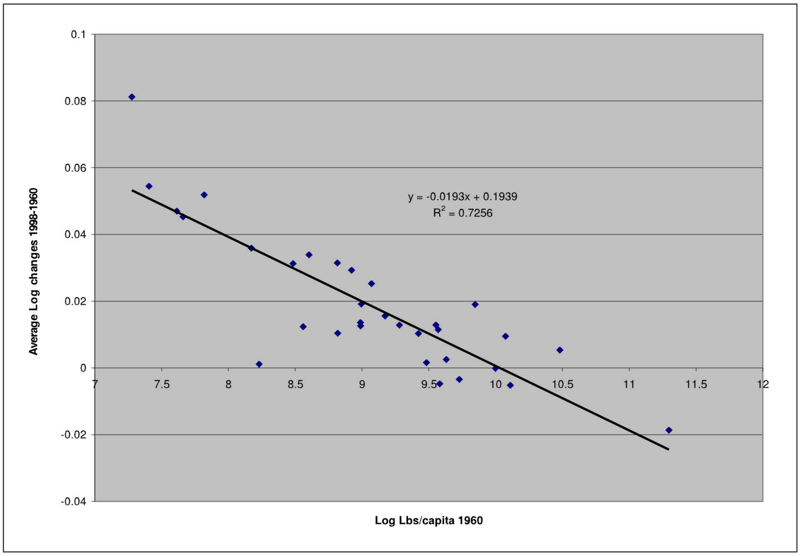

Figure 9: DeLong's Critique

But even if we take figure 9 at face value, it may in fact reveal nothing causal about convergence but instead be a manifestation of regression towards the mean. This critique, was initially put forward by Friedman (1992), and was developed more fully in a series of papers by Danny Quah (see especially Quah (1993)) and Durlauf and Quah (1999). The basic

[21] While some carbon abatement occurs as a joint product of other abatement efforts, the time profiles for carbon and the set of highly regulated pollutants are very different.

[22] The additional countries are Venezuela, Uruguay, South Africa, Saudi Arabia, Puerto Rico, Israel, Hong Kong, Barbardos, Bahamas and Argentina.

criticism (in terms of our variable emissions per person) is that if our cross-country observations on emissions per person were independent draws from a common and time invariant distribution, then countries having a high draw in 1960 are likely to have a lower draw in 1998. Countries with a low draw in 1960 are likely to have a higher draw in 1998. As a consequence a scatter plot of country emission growth rates against initial 1960 values will show a negative relationship but this "β convergence result" is consistent with many stable and non-degenerate long run distributions for emissions per unit output. Friedman notes that if regression towards the mean was the only force operating then a scatter plot of growth rates against terminal 1998 values should show a strong positive relationship. To investigate we followed Friedman (1992) and plotted emission per capita growth rates against 1998 levels. The relationship is still strongly negative. To go further we followed both Quah (1993) and Friedman (1992) and investigated other moments of the distribution. We examined the time profiles for log emissions per person and calculated the point in time variances across the sample. These two exercises showed a great deal of convergence in the distribution.

In total, these additional checks make us reasonably confident that the convergence we find in the data is not due to sample selection, measurement error, or regression towards the mean. The concerns of Durlauf and Quah (1999) and Durlauf and Johnson (1995) regarding convergence across a very heterogenous worldwide sample are largely moot here given our select sample of countries. The additional issues raised by Durlauf and Quah (1999) regarding the interpretation of cross country growth results as tests of new versus old growth theory, the treatment of endogenous regressors, the fragility of estimates, and the addition of ad hoc regressors to proxy for the free parameters of the production function would of course be relevant to any extension of our work.

4.2 International Evidence

The starting point for our analysis was 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 are a relatively small share of overall economic activity. In Table 3 we present the available evidence from European countries on these same three statistics for four of the pollutants we considered in Figure 1.

We focus on European evidence because of data limitations. The table presents summary statistics for the average yearly percentage change in emissions per unit GDP over the 1980-2001 period. As well, 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 country averages for pollution abatement costs as a fraction of GDP over the 1990-2000 period for these same countries.

There are two remarkable features of the data. The first is the massive reduction in emissions per unit of output over the period. These 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 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.

Table 3: International Evidence

Countries	NOx	Peak	SOx	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	.9
Ireland	-2.7	2000	-7.8	<1980	-7.0	1990	-6.3	1990	.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	.6
Portugal	1.0	2000	-2.5	1999	-3.4	1995	1.1	1997	.6
U.K.	-4.5	<1980	-9.4	<1980	-5.9	<1980	-4.9	1990	1.5
Average	-4.0	n.a.	-9.7	n.a.	-5.4	n.a.	-4.5	n.a.	1.3

Notes: Data on particulates is unavailable. Table 3 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. Pollution abatement costs are taken from the OECD publication "Pollution abatement and control expenditures in OECD countries", Paris: OECD Secretariat, See the data appendix for details.

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 roughly consistent with an EKC.[23] We have of course argued that the first two features of the data imply a large role for technological progress in abatement, but rapid technological progress in abatement, when coupled with the convergence properties of the Solow model, produce the third feature of the data.

4.3 What is g_A?

Aggregate models of economic activity make heroic assumptions to bring into sharp focus relationships that may otherwise be obscured Our analysis is no different. Our use of an aggregate measure for technological progress in both abatement and goods production surely hides many processes at work in the economy. Changes in the composition of national output and private consumption, fuel mix changes, and changes in factor quality over time are all partly responsible for the time profile of emissions to GDP that we have observed over the last fifty years. And many sorts of changes, including regulatory ones, lie behind what we have called technological progress in abatement. But whether this is a good or misleading way to think about the growth and environment relationship does not rest on whether this characterization is literally true, but whether it helps us identify a key force at work.

Our review of current empirical evidence suggests a key role for technological progress in abatement. We note that most if not all EKC studies find a strong and persistent time effect driving emissions downward. These time effects are not small and reduce emissions by significant amounts each year.[24] More direct evidence is contained in studies that decompose the change in pollution emissions into scale, composition and technique effects. For example, Selden et al. (1999) provide a decomposition of the change in US air pollution emissions over the 1970 to 1990 period. Using data on 6 criteria pollutants they divide the change in

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

[24] The interested reader should take his or her favourite EKC study and conduct the following experiment. Calculate the number of years it would take for an average developing country to move from low income to high income status if growth in per capita income were rapid - say 5% per year. Calculate what the implied income gain would mean in terms of reduced emissions/concentrations. Then calculate using the coefficient estimate on time in the same EKC regression the implied reduction in emissions/concentrations that would occur via time related effects over this same interval. Compare the magnitude of these two changes. In the cases we have investigated, time related effects are often ten times larger than the changes created by income growth.

emissions into scale, composition and three types of technique effects. For all six criteria pollutants (lead, sulfur dioxide, nitrogen oxide, volatile organic compounds, carbon monoxide and particulates) reductions in emissions per unit fuel combusted, and reductions in emissions per unit output were key in driving emissions downwards. While changes in the composition of output lowered emissions for some pollutants, it raised them for volatile organic compounds and carbon monoxide. And while changes in energy intensity and the mix of energy sources helped lower the emissions of some pollutants, for all pollutants studied emissions would have risen in the absence of the change in techniques discussed above.

Related work by Bruvoll and Medin (2003) find similar results using Norwegian data. They report that their analysis reveals that "air pollution has not followed the pace of economic growth. This is mainly due to new technologies"; and that "changes in production structure or composition of energy types have been of less importance to the development of energy related emissions", p. 42.

Overall these results suggest to us that a large component of the change in the emissions to output ratio must be technological progress. Composition changes have not been large enough, technology or technique effects have been found to be key, and abatement costs are just too small to be largely responsible for the large reductions in emissions per unit of output experienced.

4.4 Optimization and Functional Forms

To what extent are our assumptions of fixed abatement or savings rates required for our results? It is well known that allowing for optimal consumption complicates but does not reverse the Solow model's convergence properties. With optimal consumption the savings rate now varies over the transition path and this may hasten or delay the speed of adjustment to the steady state. One concern may be that optimal abatement could shift over the transition path in such a way as to rule out the EKC profile we derived. To investigate note that if the optimal k is bounded, then emissions have to fall in the long run if $G_E < 0$. Therefore, falling emissions and rising environmental quality are guaranteed. In the short run emissions will at first rise as long as the abatement is not initially too aggressive relative to the pace of growth. Many different assumptions will generate this result. In our fixed rule case we generated this result by assuming the initial capital stock $k(0)$ was less than k^T. The small initial capital ensured growth was rapid and this overwhelmed technological progress in abatement. In an optimizing framework similar forces are at work but we need to add assumptions on abatement (to ensure its growth is not too rapid), consumption (to make sure output growth is rapid enough initially) and marginal damage (to control the planner's response to rising pollution).

One method is to assume marginal damage from emissions is not too high when $k(0)$ is small so that abatement is not undertaken initially. For example we could assume the marginal product of abatement is bounded above and the damage from pollution convex in emissions as in Stokey (1998) or Brock and Taylor (2003a). In this situation the first unit of emissions has zero marginal damage while abatement has a finite cost (determined by the shadow value of capital). These authors show emissions at first rise only to be offset by abatement or a combination of abatement plus technological progress in the future.

Alternatively, we could let the abatement function satisfy Inada type conditions so that abatement is always undertaken, but then adopt assumptions to ensure that sacrifices in consumption are not too costly (so growth is initially rapid) and pollution not too damaging (to make policy responses weak). In short many sets of reasonable assumptions on abatement and utility will generate the result that pollution can at first rise with growth. Assuming sufficiently strong technological progress in abatement ensures that pollution will fall eventually.

A final concern of readers may be our use of a Cobb-Douglas aggregator for output. Although this functional form is commonly used in growth theory and elsewhere, it is important to understand its limitations. Its benefit to us outweighed its costs because it allowed us to derive simple closed form solutions for quantities of interest. In many cases our results carry through although they are more difficult to prove and less transparent to the reader. For example, our key result that an EKC relationship arises from the interplay of diminishing returns and technological progress in abatement remains true. To verify consider the dynamics of environmental quality X and income per capita with a general intensive production function $f(k)$. Assume $f(k)$ satisfied the Inada conditions, and write the dynamic system for k and X as:

$$\dot{k} = sf(k)[1-\theta] - [\delta + n + g]k \tag{26}$$

$$\dot{X} = c_0 \exp[G_E t] f(k) - \eta X \tag{27}$$

where $c_0 > 0$ and $G_E < 0$. To show the environment must at first worsen evaluate 27 at $t = 0$. At $t = 0$ the environment is initially pristine, $X(0) = 0$, and the initial capital stock is not zero, $k(0) > 0$. Equation 27 shows the environment must at first worsen. X has to be growing at least initially. To examine the rest of the transition path recall $k(t)$ is increasing in time until it reaches k^*. We can use this fact to bound the path for X noting:

$$\overset{\bullet}{X} = c_0 \exp[G_E t] f(k) - \eta X < \overset{\bullet}{X} = c_0 \exp[G_E t] f(k*) - \eta X \tag{28}$$

For any $t > 0$, $X(t)$ must be below the solution to the ordinary differential equation $\overset{\bullet}{X} = c_0 \exp[G_E t] f(k*) - \eta X$, $X(0) = 0$. This ordinary differential equation has a closed form solution showing $X(t)$ tends to zero as t goes to infinity. Using the inequality in 28 we conclude X must at first rise, but then fall as before. Proving a similar result for $E(t)$ is left to the reader. The EKC prediction of the model is not limited to our Cobb-Douglas formulation.

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 ten 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 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.

In support of our argument we marshalled several pieces of evidence. We presented evidence that the U.S. emission to output ratio has fallen at a roughly constant rate for almost 50 years; that this reduction predates the peak of emissions; and that abatement expenditures while growing since the early 1970s have remained a fairly constant 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. 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 produced several testable restrictions and led to the estimation of key parameters. While we view our empirical work as preliminary, it lends further support to our view that the same ongoing dynamic processes responsible for income growth and convergence are also at play in determining the EKC finding and emission convergence. The evidence for convergence is quite strong, and well in accord with the theoretical predictions of the Green Solow Model.

The very simplicity of our model calls out for future work to qualify, elaborate or perhaps refute our thesis. The model is singularly successful in identifying technological progress in abatement as a potential key to much of the income and pollution data, but no theory of innovation nor optimal regulation was provided. Our formulation is consistent with a world where governments gradually tighten emission standards over time, but we can only speculate as to whether this gradual march forward in regulation is caused by income growth and whether gradually tightening standards are the impetus for ongoing technical improvements in abatement. Our empirical work, as we state, is preliminary and our method of estimating technological progress in abatement crude. Moving forward on both empirical and theoretical fronts is surely a worthy goal for future research.

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