On the mechanics of the “Green Solow Model”[1]

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Abstract

Brock and Taylor (2010) argue that the Environmental Kuznets Curve (EKC) is driven by falling GDP growth rates associated with a Solow type convergence. I test the importance of their mechanism by performing a “pollution accounting” exercise that decomposes emissions data into pollution intensity and GDP growth effects. The “Green Solow” framework assumes that emission intensities decline at a *constant* rate and hence that all changes in emissions growth rates are driven by changes in GDP growth rates. Yet, in the data, emission intensities are hump-shaped, implying *declining* emission intensity growth rates. Furthermore, this decline is up to an order of magnitude larger than changes in GDP growth. By assigning all the weight to GDP growth, the Green Solow model misses the largest driver of emissions. Models aiming to explain the EKC, should thus focus on explaining hump-shaped emission intensities and consequently falling emission intensity growth rates.

Keywords: Environmental Kuznets Curve; Emissions; Emission Intensity; Structural Transformation; Pollution Accounting

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1 Introduction

In a recent paper, Brock and Taylor (2010) argue that the Environmental Kuznets Curve (EKC) - a hump-shaped empirical relationship between emissions and income per capita - is driven by falling GDP growth rates associated with Solow type convergence to a balanced growth path. In this paper, I perform a "pollution accounting" exercise that empirically tests the importance of their mechanism as a driver of emissions. In a decomposition of emission data into pollution intensity and GDP growth effects, I show that falling emission intensity growth rates can dominate Brock and Taylor's convergence effects by more than an order of magnitude. This suggests that models of emissions should perhaps focus on explaining large changes in emission intensity growth rates, rather than focusing entirely on explaining changing GDP growth rates.

The analysis in this paper is based on a "pollution accounting" exercise akin to the growth accounting of Solow (1957). I follow Brock and Taylor (2010), in assuming that man-made emissions are directly related to the production process.[2] Higher output is associated with higher emissions, unless production of additional units of output becomes cleaner. The simplest way to capture this relationship for an economy at time t, is the following pollution "production function":

$$P_t = N_t Y_t, \tag{1}$$

where, P_t represents the total emissions of an economy, Y_t is the total output of an economy and N_t is the quantity of emissions released per unit of output (referred to as the emission intensity). Taking logarithms of the above equation and differentiating with respect to time, gives a relationship between the growth rate of emissions, $g_{P,t}$, the growth rate of GDP, $g_{Y,t}$, and the growth rate of emission intensity $g_{N,t}$:

$$g_{P,t} = g_{Y,t} + g_{N,t}. \tag{2}$$

Emissions increase over time if and only if $g_{P,t} > 0$ and fall if and only if $g_{P,t} < 0$. As such, an EKC can occur if and only if $g_{P,t}$ falls from above to below zero over time. According to the above decomposition, such a decline in $g_{P,t}$ can occur if either $g_{Y,t}$ or $g_{N,t}$ (or both) decline over time. Brock and Taylor (2010) assume that $g_{N,t}$ remains constant and negative (due to exogenous technological improvements in abatement technology) and then show that a decline in $g_{Y,t}$ generated by capital accumulation drives the decline in $g_{P,t}$.[3] The point of this

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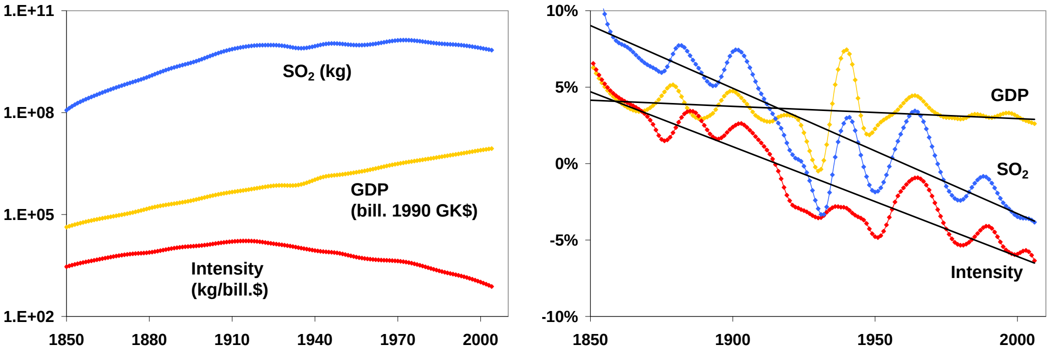
[2] This is a fairly common assumption also made by Copeland and Taylor (1994), Stokey (1998), Aghion and Howitt (1998) among others.

[3] Economies with very low capital stocks grow quickly and have a $g_{Y,t}$ high enough to outweighs the (constant) negative $g_{N,t}$, resulting in a positive $g_{P,t}$ and growing emissions. As economies accumulate capital and converge to their balanced growth path, their GDP growth rates slow, resulting in a $g_{Y,t}$ that falls over time. If $g_{Y,t}$ slows enough so the economy grows slower than the rate at which emission intensity declines, $g_{P,t}$ becomes negative and emissions fall. In the Green Solow framework, falling GDP growth rates are thus entirely responsible for the EKC-type emission profile.



(a) Emissions, GDP and Intensity.

(b) Emissions, GDP and Intensity growth.

Figure 1: SO_2 Emissions, Intensity and GDP levels/growth rates in the US, 1850-2006.

paper is to show that, in the data, it is $g_{N,t}$ that falls significantly with time and income, whilst $g_{Y,t}$ remains relatively constant. Whilst the mechanism proposed by Brock and Taylor (2010) remains valid, quantitatively it plays only a limited role.

An example of this can be seen in Figure 1, which shows the above decompositions in log-levels and in growth rates for sulfur dioxide in the US. A concave EKC for sulfur is visible in the first panel. GDP growth, however, is nearly constant over the entire period. Instead, the concavity of emissions is driven by the concavity of emission intensity. In the panel to the right, it becomes clear that the decline in emission growth rates stems predominantly from the declining emission intensity growth rates, rather than from the relatively flat GDP growth rates.

In section 2, I briefly describe the Green Solow model and demonstrate that within its framework the EKC arises solely from dynamics in GDP growth rates: $g_{Y,t}$ falls over time, whilst $g_{N,t}$ is assumed constant and negative. This last assumption implies emission intensities that decline at a constant rate over time. In section 3, I show that this implication is not borne out by the data: emission intensities are in fact hump-shaped for a wide range of countries and pollutants, implying falling emission intensity growth rates. In section 4, I perform a pollution accounting exercise which demonstrates that changes in $g_{N,t}$ (over time and income) are an order of magnitude larger than changes in $g_{Y,t}$. Whilst slowing GDP growth undoubtedly contributes to falling emissions, slowing emission intensity growth is much more important. Models that aim to explain the EKC, must - first and foremost - explain the hump-shaped intensity curve and hence explain falling intensity growth rates. Finally, in section 5, I suggest a simple model of structural transformation from agriculture to non-agriculture as one (but certainly neither the only nor the definitive) mechanism capable of generating both a hump-shaped EKC curve and a hump-shaped emission intensity curve.

2 The Green Solow Model

Brock and Taylor (2010) present a very simple extension of the traditional Solow model. For simplicity, both savings rates and abatement choices are assumed to be exogenously set. Output is assumed to be produced using capital (K_t) and labor (L_t) by a constant returns to scale and strictly concave production function, $F(K_t, B_t L_t)$, where B_t is the productivity of labor. Capital is accumulated at a constant savings rate s and depreciates at a fixed rate δ. Pollution is assumed to be generated directly by output. If left unabated, a unit of output will generate Ω_t units of pollution at every point in time. However, the economy can devote a constant (and exogenous) fraction of output, $0 \leq \theta \leq 1$, to abate pollution. After abatement, a unit of output generates $a(\theta)\Omega_t$ units of pollution, where $a(\theta)$ is an abatement function that is assumed to satisfy $a(0) = 1$ as well as $a'(\theta) < 0$ and $a''(\theta) > 0$. Thus, abatement has a positive but diminishing marginal impact on pollution reduction. The labor force, L_t, is assumed to grow at a constant rate n. Labor productivity, B_t, is assumed to grow at a constant and exogenous growth rate g. There also exists exogenous technological progress in abatement, that lowers Ω_t at a constant rate $g_A > 0$. The model is given by:

$$Y_t = (1-\theta)F(K_t, B_t L_t)$$

$$\dot{K}_t = sY_t - \delta K_t$$

$$P_t = a(\theta)\Omega_t F(K_t, B_t L_t)$$

$$\dot{L}_t = nL_t \qquad \dot{B}_t = gB_t \qquad \dot{\Omega}_t = -g_A \Omega_t,$$

where a dot above a variable represents the partial derivative with respect to time. In particular, notice that emission intensity, $N_t \equiv P_t / F(K_t, B_t L_t)$, is simply declining at the constant exogenous rate of technological progress in abatement, g_A, that is independent of the level of abatement, θ.

The main departure from the standard Solow model is the assumption that pollution is co-produced with every unit of output. A second departure, is the assumption that some fraction of income can be devoted to abatement. Notice however, that neither one of these assumptions fundamentally influences the dynamics of the standard Solow model. The production of pollution does not affect growth of output, whilst the extent of abatement will affect the level of GDP, but not its growth path. In particular, the model can be solved like the regular Solow model, by re-writing it in effective units per capita as follows:

$$y_t = (1-\theta)f(k_t)$$

$$\dot{k}_t = s(1-\theta)f(k_t) - (\delta + n + g)k_t$$

$$p_t = \Omega_t a(\theta) f(k_t),$$

where $k_t = K_t/B_tL_t$, $y_t = Y_t/B_tL_t$, $p_t = P_t/B_tL_t$ and $f(k_t) = F(k_t, 1)$. Next, for simplicity assume that $F(K, L) = K^{\alpha}L^{1-\alpha}$. Then, given a fixed θ, it follows immediately that starting from any $k(0) > 0$, the economy converges to a unique capital per effective worker level, k^*, just as in the Solow model. On the balanced growth path aggregate GDP, consumption and capital all grow at rate $g_Y = g_C = g_K = g + n$, whilst their corresponding per capita magnitudes grow at rate $g_y = g_c = g_k = g$. Finally, pollution grows according to $g_P = g + n - g_A$. Off the BGP, the growth rate of the economy and emissions depends on the level of capital stock. In particular, it is easy to show that:

$$\frac{\dot{k}_t}{k_t} = sk_t^{\alpha-1}(1-\theta) - (\delta + n + g) \tag{3}$$

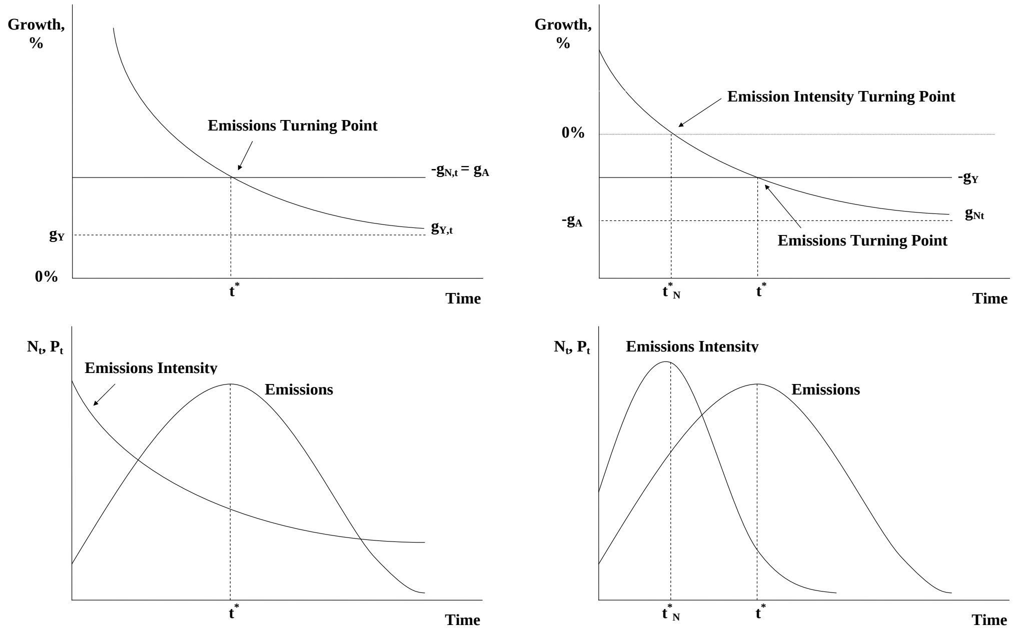
and

$$g_{P,t} \equiv \frac{\dot{P}_t}{P_t} = g_{Y,t} - g_A = (g + n + \alpha\frac{\dot{k}_t}{k_t}) - g_A, \tag{4}$$

where $g_{Y,t} = g + n + \alpha\frac{\dot{k}_t}{k_t}$, is the growth rate of output off the BGP. As in the standard Solow model, if the effective-units economy starts with a capital stock smaller than the steady state level ($0 < k_0 < k^*$), the economy accumulates capital ($\frac{\dot{k}_t}{k_t} > 0$) until it converges to the steady state ($\lim_{t\to\infty} k_t = k^*$), at which point the economy stops accumulating capital ($\lim_{t\to\infty} \frac{\dot{k}_t}{k_t} = 0$). Notice also that whilst the changing rate of capital accumulation is generating the dynamics of the model, the only effect of capital accumulation is its impact on GDP growth rates. Consequently, the economy is growing faster *off* the BGP than it does *on* the BGP (i.e. $g_{Y,t} > g_Y$). Furthermore, if (for given parameter values) it is assumed that $g_P = g + n - g_A < 0$, then, with low enough initial capital stock, there exists a t^* such that for $t < t^*$, $g_{P,t} = g_{Y,t} - g_A > 0$, whilst for $t > t^*$, $g_{P,t} = g_{Y,t} - g_A < 0$. Emissions follow an EKC type profile, peaking at t^*.

This process is demonstrated in the first column of Figure 2. Countries starting at low levels of capital grow faster than they do on their BGP. For countries with low enough levels of initial capital, improvements in emission intensity are not enough to outweigh the extra pollution caused by faster growth of GDP - this results in rising total emissions ($g_{P,t} = g_{Y,t} - g_A > 0$, for $t < t^*$). As capital is accumulated, GDP growth eventually slows enough for improvements in emissions intensity to outweigh the additional pollution created during the production of output - resulting in falling emissions ($g_{P,t} = g_{Y,t} - g_{A,t} < 0$, for $t > t^*$). Depending on the chosen parameters, capital accumulation and constant growth in abatement technology can result in an EKC (although whether an EKC is observed depends fundamentally on parameters).

Although the dynamics of the EKC in the Green Solow framework are driven by capital accumulation, this manifests itself through the dynamics of GDP growth rates. Neither capital accumulation nor any other choice variable impacts emission intensity, which declines at



(a) Brock and Taylor (b) Possible alternative

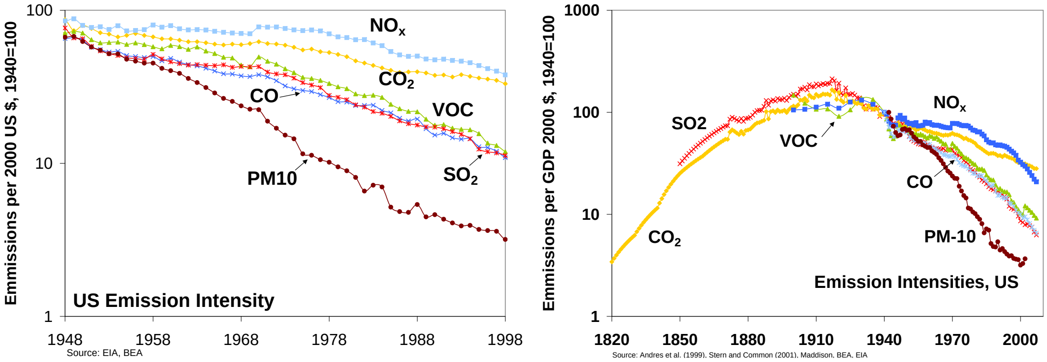
Figure 2: The EKC according to Brock and Taylor (2010) and a possible alternative.

a constant rate entirely due to constant and exogenous technological progress in abatement technology. In what follows I show that - in the data - the influence of dynamics of GDP are secondary in determining the shape of the EKC relative to the dynamics of the emission intensity growth rates. In particular, I show that the world is more like the second column of Figure 2: GDP growth rates are relatively flat over time, whilst emission intensity growth rates decline by a large amount. This decline in intensity growth rates manifests itself through a hump-shaped emission intensity which peaks when intensity growth rates fall to zero and can give rise to an EKC (like in the Green Solow model) if intensity growth rates drop to a low enough level.

3 Stylized Facts

3.1 Development of Emission Intensity in the US

The mechanism driving emissions within the Green Solow model is declining GDP growth rates caused by convergence plus constant rates of technological progress in abatement. The implication of this second assumption is that emission intensity growth rates fall at a constant rate. Brock and Taylor (2010) motivate this by showing US data for the 1948-1998 period, which I reproduce in Figure 3(a). The figure shows indices of US emissions of various pollutants (with



(a) Brock and Taylor (2010):US Emission intensities, 1948-1998.

(b) This paper: US emission intensities, 1820-2007.

Figure 3: US emission intensities

1940=100) per dollar of US GDP (in 2000 chained US dollars). The intensities under consideration are nitrogen oxides (NO_x), carbon dioxide (CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), volatile organic compounds (VOC) and particulate matter of less than ten microns (PM10).[4] I adopt a log-scale for ease of reading and to allow us to interpret the slope of the graph as an average growth rate. To a first approximation, it is true that the slopes of these graphs are constant as Brock and Taylor (2010) assert. Nonetheless, the rate of decline in intensity is larger in the second part of the data than in the first. Table 1 shows results for the regression of the log of emission intensities and the log of GDP versus time for 1948-1973 (top half) and 1973-1998 (bottom half). The coefficient on the year in each regression can be interpreted as the average growth rate of intensities and GDP over the period in question. We can see that in both periods emission intensities decline but that the rate of decline is between 0.7 to 2.9 percentage points larger in the second period. This - depending on pollutant - is equal or up to 4.14 times larger than the change in GDP growth rates. Importantly, these changes are not a consequence of the chosen time period. In Appendix 7.1, I subdivide the data into quartiles and show that the absolute change in intensity growth rates still outweighs the change in GDP growth rates for almost all periods and pollutants.

Finally, Figure 3(b) extends the data backwards and forwards in time.[5] It becomes very clear that emission intensities are not declining at a constant rate, but rather trace out a hump

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[4] The source of GDP data is the BEA. The pollution data is from the EPAs 1998 National Pollution Emission Trends report, available at http://www.epa.gov/ttnchie1/trends/trends98/trends98.pdf. Like Brock and Taylor (2010) I drop fugitive dust sources from the data for PM10, since it is not available for the entire period.

[5] I use the EPAs 1998 National Pollution Emission Trends report to extend all the data forward in time and all the data except CO_2 and SO_2 backwards in time. For carbon and sulfur dioxide I extend backwards using Andres et al. (1999) and Stern (2005) respectively. GDP data also now comes from Maddison (2007) instead of the BEA. Missing GDP data between 1820-1870 has been linearly interpolated.

Years	GDP	PM10	CO2	CO	NO	SO2	VOC
1948-1973	0.037***	-0.055***	-0.011***	-0.025***	-0.003***	-0.022***	-0.019***
	(0.000)	(0.002)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)
1973-1998	0.030***	-0.062***	-0.023***	-0.043***	-0.029***	-0.048***	-0.048***
	(0.000)	(0.002)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)
Difference	0.7%	0.7%	1.2%	1.8%	2.6%	2.6%	2.9%
Rel. to GDP	-	1.00	1.71	2.57	3.71	3.71	4.14

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 1: Average growth rate in intensity/GDP in the US for 1948-1973 and 1973-1998.

shape. This implies that growth rates of emission intensities fall from above zero (when emission intensity is rising) to below zero (when emission intensity is falling) over time. This suggests that understanding changes in emission intensity growth may be especially important in countries that are at earlier stages of development.

3.2 Development of Emission Intensity Across Countries

The hump shape in emission intensity is not restricted to the US and is a regular feature of almost all of the world's major emitters. In this section, I consider a baseline panel of carbon and sulfur dioxide emission intensities for 35 countries for the period 1820-2005 (given data availability).[6] The set of countries consists of those that either belong to the OECD or are in the top 25 CO_2 or SO_2 emitters. I focus on this sample for three reasons. First, these were the most relevant countries to global emissions over the last two centuries accounting for between 82% and 83% of global CO_2 and SO_2 emissions respectively. Second, OECD countries have long time series of data available which provides a more accurate picture of emission trends and helps avoid mismeasurement due to business cycles or other unrelated fluctuations in the data. Finally, focusing primarily on OECD countries ensures that data is of a higher quality. None of our subsequent results however, depend on the chosen sample.[7]

A summary of the baseline data is shown in Figure 4(a) which plots (the log of) total CO_2 emissions per dollars of GDP for 35 major emitters versus each country's GDP per capita, for the period 1820-2005 (given data availability). Figure 4(b) plots (the log of) total SO_2 emissions per dollar of GDP for the same countries versus each country's GDP per capita, for the years 1850-2002. Despite some variance in levels, emission intensity of both CO_2 and SO_2

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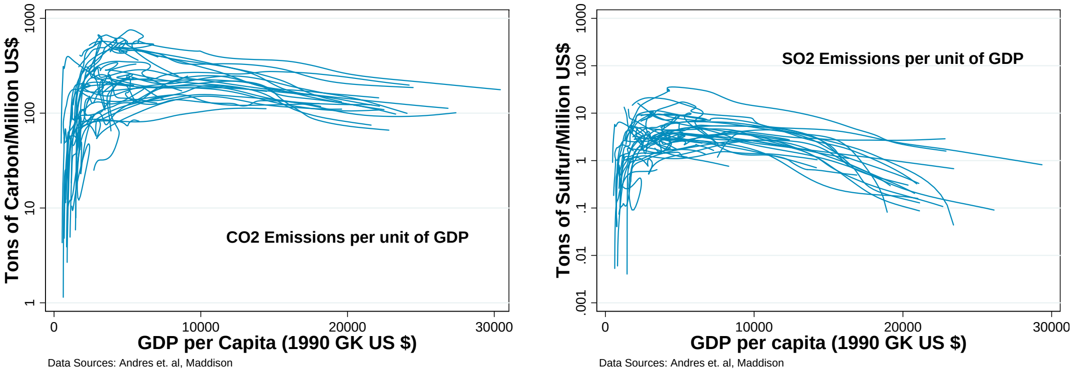
[6] Due to data constraints I treat the former Soviet Union as one region over the entire period. In principle, this means that the sample consists of 44 countries. The source of the data is Andres et al. (1999) (for CO_2), Stern (2005) (for SO_2) and Maddison (2007) (for GDP and GDP per capita). See Appendix 7.2 for more details on data construction, possible issues as well as summary statistics.

[7] The Appendix shows that all results hold in a full sample of data as well as in the same balanced-panel of 94 countries for 1960-1998 that was used by Brock and Taylor (2010).



(a) 35 Emitters: Carbon Dioxide Emission Intensity, 1820-2007

(b) 35 Emitters: Sulfur Dioxide Emission Intensity, 1850-2000

Figure 4: CO_2 and SO_2 emission intensities.

rises initially, after which it begins to fall. We observe a hump shape pattern or a sideways-L pattern (i.e. one where emission intensity grows very fast initially and then remains roughly constant) in 32 out of the 35 countries for CO_2 data and 31 out of 35 countries in SO_2 data. This implies that almost all countries experienced a large decline in emission intensity growth rates. Countries that exhibited a hump shape saw their emission intensity growth rates decline from above to below zero, whilst those which exhibited a sideways-L pattern saw their emission intensity growth rates decline, but remain roughly at zero.

Previous Literature The hump-shaped pattern of emission intensity for carbon dioxide is relatively well known. Tol et al. (2009) examine this relationship for the United States for the 1850-2002 period. Lindmark (2002), Kander (2002) and Kander and Lindmark (2004) demonstrate that this relationship holds for Sweden. Bartoletto and Rubio (2008) find evidence of a similar pattern in Italy and Spain. Finally, in the largest study of the sort, Lindmark (2004) examines CO_2 emission intensity in forty six countries and finds that the hump shape is a feature in most of those economies. To my knowledge, the current study is the first to document a similar fact for sulfur dioxide intensities. More importantly however, in the next section, I quantify the role of changing emission intensity and GDP growth rates, and show that changes in emission intensity growth are key in the formation of the EKC.

4 International Pollution Accounting

The above figures suggest that growth rates of emission intensities fall from above to below zero in a wide range of countries. In this section, I perform a simple pollution accounting exercise which quantifies the rate of this decline and demonstrates that - over time - changes in emission intensity growth rates have dominated changes in GDP growth rates and as such were much more important to driving emissions.

Recall that an EKC occurs in a country if and only if $g_{P,t}$ falls from above to below zero over time. According to the decomposition shown in equation 2, growth rates of pollution at any point in time are equal to the sum of growth rates of intensity and GDP:

$$g_{P,t} = g_{Y,t} + g_{N,t}. \tag{5}$$

This paper asks how fast the individual components on the right-hand side of the above equation have changed over time in the data, and which one is a more important driver of changes in $g_{P,t}$. The simplest way to measure changes in growth rates over time is to estimate the following:

$$g_{j,t} = c_j + \beta_j t \text{ for } j = P, N, Y, \tag{6}$$

where β_j is the average rate of change of growth over time. Importantly, this equation only serves to *measure* the particular rate of change of growth and does *not* hinge on a specific, underlying economic theory. Substituting (6) for each of the growth terms in the decomposition found in identity (5) implies that:

$$\beta_P = \beta_N + \beta_Y. \tag{7}$$

Thus, changes in emissions growth rates (β_P) are accounted for by changes in either emissions intensity growth rates (β_N) or changes in GDP growth rates (β_Y), i.e. $\frac{\beta_N+\beta_Y}{\beta_P} = 1$. The contribution of changing emission intensity growth rates is $\frac{\beta_N}{\beta_P}$, whilst that of GDP growth rates is $\frac{\beta_Y}{\beta_P}$. If the intensity or GDP growth rates are constant over time, then the coefficients β_N and β_Y will not be statistically different from zero. Positive or negative coefficients however, imply an increasing or a decreasing growth rate over time respectively. Recall from equation (4) that the Green Solow framework assumes that growth rates of intensity do not change over time ($\beta_N = 0$), and that output growth rates decline over time ($\beta_Y < 0$). Thus, the decline in emission growth rates in the Green Solow framework is driven entirely by falling GDP growth rates, so that $\beta_P = \beta_Y$. This paper shows that whilst GDP growth rates can indeed decline over time ($\beta_Y < 0$), intensity growth rates are not constant but *also* decline over time ($\beta_N < 0$). Furthermore the decline in intensity growth rates is much larger than the decline in GDP growth rates ($|\beta_N| > |\beta_Y|$) and therefore accounts for more of the decline in emissions growth rates, i.e. $\frac{\beta_N}{\beta_P} > \frac{\beta_Y}{\beta_P}$.

Table 2 shows the estimates of β_j for $j = P, N, Y$ in each country for both the carbon and sulfur baseline samples.[8] Growth rates in carbon and sulfur emissions decline in all countries

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[8] Notice that the growth rates of GDP can differ between the CO_2 and SO_2 columns, since the sulfur and carbon samples do not cover the same times periods. See the Appendix for details on the data.

	CO2	Int	GDP	SO2	Int	GDP
Australia	-4.60***	-4.54***	-0.07	-2.07***	-0.55	-1.52***
	(0.42) 0.45	(0.39) 0.49	(0.25) 0.00	(0.67) 0.06	(0.82) 0.00	(0.38) 0.10
Austria	-0.30	-1.64*	1.34***	-8.97***	-10.43***	1.45***
	(1.11) 0.00	(0.96) 0.02	(0.43) 0.07	(1.28) 0.27	(1.05) 0.43	(0.45) 0.07
Belgium	-2.80***	-3.09***	0.28	-6.83***	-7.26***	0.43*
	(0.36) 0.28	(0.21) 0.58	(0.22) 0.01	(0.67) 0.41	(0.55) 0.54	(0.24) 0.02
Brazil	-0.45	-0.50	0.05	-1.99	-4.10***	2.12***
	(1.02) 0.00	(0.80) 0.00	(0.54) 0.00	(1.26) 0.02	(1.28) 0.07	(0.37) 0.20
Canada	-8.56***	-8.70***	0.14	-10.40***	-10.63***	0.23
	(0.73) 0.51	(0.67) 0.56	(0.33) 0.00	(0.45) 0.81	(0.32) 0.90	(0.34) 0.00
China	-30.63***	-39.96***	9.33***	-43.72***	-51.67***	7.95***
	(7.68) 0.23	(7.01) 0.38	(0.88) 0.68	(7.87) 0.38	(7.18) 0.50	(0.99) 0.56
Denmark	-5.29***	-5.56***	0.26*	-13.17***	-13.64***	0.47***
	(0.34) 0.61	(0.27) 0.73	(0.15) 0.02	(1.72) 0.28	(1.66) 0.31	(0.17) 0.05
Finland	-1.99*	-2.89***	0.91***	-10.00***	-10.93***	0.93***
	(1.19) 0.02	(1.01) 0.05	(0.22) 0.11	(1.32) 0.29	(1.20) 0.37	(0.23) 0.11
France	-4.08***	-5.23***	1.16***	-6.76***	-8.39***	1.63***
	(0.34) 0.44	(0.18) 0.82	(0.25) 0.11	(0.67) 0.41	(0.48) 0.67	(0.36) 0.12
Germany	-81.26***	-76.31***	-4.95***	-13.13***	-13.43***	0.30
	(9.01) 0.86	(9.20) 0.84	(0.27) 0.96	(1.42) 0.36	(1.36) 0.40	(0.39) 0.00
Greece	-7.04	-7.09**	0.05	-2.67	-2.38	-0.28
	(4.36) 0.03	(3.52) 0.04	(1.23) 0.00	(4.77) 0.00	(4.27) 0.00	(1.31) 0.00
Hungary	-26.68***	-17.02***	-9.66***	-38.95***	-26.37***	-12.58***
	(2.05) 0.75	(1.09) 0.81	(1.50) 0.42	(1.77) 0.90	(1.82) 0.80	(1.32) 0.63
India	-2.50***	-7.40***	4.90***	-1.45**	-5.85***	4.40***
	(0.75) 0.09	(0.57) 0.59	(0.34) 0.63	(0.59) 0.05	(0.46) 0.59	(0.36) 0.57
Indonesia	-11.16***	-11.90***	0.75	-12.37***	-15.94***	3.57***
	(2.99) 0.20	(2.48) 0.30	(1.36) 0.01	(2.97) 0.14	(2.82) 0.23	(0.53) 0.30
Iran	-70.08***	-57.61***	-12.46***	-2.65	10.82***	-13.48***
	(18.17) 0.22	(18.62) 0.16	(2.67) 0.30	(2.92) 0.02	(2.91) 0.22	(3.16) 0.28
Ireland	0.92	-6.92***	7.84***	-9.69***	-17.77***	8.08***
	(0.91) 0.01	(0.74) 0.53	(0.46) 0.79	(1.90) 0.25	(1.79) 0.55	(0.43) 0.81
Italy	-4.15***	-5.62***	1.47***	-18.05***	-19.72***	1.66***
	(0.86) 0.14	(0.67) 0.33	(0.35) 0.11	(4.55) 0.10	(4.50) 0.12	(0.36) 0.13
Japan	-7.35***	-8.73***	1.38**	-15.44***	-17.18***	1.74***
	(0.88) 0.35	(0.55) 0.67	(0.64) 0.04	(1.39) 0.49	(1.32) 0.57	(0.61) 0.06
Korea Rep.	-55.61***	-53.87***	-1.75	-93.14***	-93.40***	0.26
	(9.32) 0.39	(9.44) 0.36	(1.24) 0.03	(22.57) 0.25	(22.50) 0.25	(1.43) 0.00
Malaysia	-0.54	10.70***	-11.24***	13.25***	8.82***	4.43***
	(3.13) 0.00	(2.60) 0.34	(1.65) 0.58	(1.72) 0.54	(1.36) 0.45	(1.02) 0.27
Mexico	-4.81***	-6.81***	2.00**	-1.87**	-4.36***	2.49***
	(1.30) 0.13	(1.03) 0.33	(0.85) 0.06	(0.90) 0.04	(0.95) 0.17	(0.66) 0.12
Netherlands	-0.87**	-2.09***	1.22***	-6.24***	-7.66***	1.42***
	(0.41) 0.03	(0.24) 0.33	(0.27) 0.11	(0.79) 0.29	(0.61) 0.51	(0.29) 0.13
New Zealand	-3.79***	-3.62***	-0.18	-6.09***	-4.36***	-1.72***
	(0.73) 0.18	(0.68) 0.19	(0.27) 0.00	(0.51) 0.52	(0.55) 0.32	(0.37) 0.14
Norway	-6.37***	-7.41***	1.04***	-12.58***	-13.74***	1.16***
	(0.62) 0.39	(0.59) 0.49	(0.12) 0.30	(0.88) 0.58	(0.80) 0.66	(0.15) 0.29
Poland	-18.13***	-13.02***	-5.11***	-33.18***	-26.11***	-7.08***
	(1.08) 0.84	(1.20) 0.69	(1.52) 0.18	(1.93) 0.86	(2.88) 0.62	(1.53) 0.30
Portugal	-2.86***	-5.10***	2.24***	-1.73***	-4.29***	2.56***
	(1.10) 0.05	(1.06) 0.15	(0.28) 0.32	(0.57) 0.07	(0.45) 0.41	(0.25) 0.43
Saudi Arabia	-116.17***	-91.39***	-24.78***	-18.76***	1.16	-19.91***
	(16.37) 0.53	(16.45) 0.41	(2.45) 0.70	(4.97) 0.23	(5.21) 0.00	(2.56) 0.56
Spain	-3.74***	-5.99***	2.25***	-3.78***	-6.07***	2.29***
	(0.74) 0.14	(0.64) 0.37	(0.31) 0.26	(0.55) 0.24	(0.42) 0.58	(0.32) 0.25
Sweden	-8.73***	-9.01***	0.28**	-14.36***	-14.47***	0.10
	(0.63) 0.54	(0.58) 0.59	(0.13) 0.03	(1.01) 0.57	(0.93) 0.62	(0.15) 0.00
Switzerland	-6.30***	-6.54***	0.24	-16.58***	-16.51***	-0.07
	(0.88) 0.26	(0.86) 0.29	(0.26) 0.01	(1.52) 0.45	(1.41) 0.48	(0.24) 0.00
Thailand	-24.52***	-20.39***	-4.13***	-88.81***	-86.37***	-2.43*
	(2.72) 0.61	(2.61) 0.54	(1.14) 0.20	(10.30) 0.61	(10.32) 0.59	(1.36) 0.06
Turkey	-3.57***	-1.93***	-1.64**	-4.30***	-2.69**	-1.61*
	(1.09) 0.12	(0.64) 0.10	(0.79) 0.05	(1.47) 0.10	(1.25) 0.06	(0.90) 0.04
USSR	-17.34***	-12.98***	-4.37***	-29.04***	-17.10***	-11.94***
	(2.28) 0.49	(1.68) 0.49	(1.22) 0.17	(1.74) 0.80	(1.58) 0.63	(1.45) 0.49
UK	-2.38***	-2.58***	0.20*	-7.07***	-7.41***	0.34**
	(0.13) 0.67	(0.11) 0.77	(0.12) 0.02	(0.56) 0.52	(0.59) 0.52	(0.15) 0.03
US	-4.80***	-4.11***	-0.68**	-7.57***	-6.90***	-0.67**
	(0.38) 0.54	(0.26) 0.65	(0.27) 0.05	(0.45) 0.68	(0.28) 0.82	(0.28) 0.04

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 2: Estimates of equation (6) by country for Sulfur and Carbon in baseline samples. Standard errors and R^2 underneath estimates. All values multiplied by 10^4 for ease of reading.

bar Ireland (for carbon) and Malaysia (for sulfur). This decline is statistically significant at the 10% level or less for 30 out of 35 countries for carbon and 32 out of 35 countries for sulfur. These negative growth rates are consistent with an EKC-type pattern of emissions. The rate of decline of the growth rate of emission intensity is negative in all the countries bar Malaysia (for both carbon and sulfur) as well as Iran and Saudi Arabia (for sulfur only). Furthermore, this decline is statistically significant at the 10% level or less in 33 out of 35 countries for carbon and 30 out of 35 countries for sulfur. Finally, notice that falling intensity growth is overwhelmingly driving falling emissions growth rates. The absolute change in the growth rate of emissions intensity is greater than the absolute change of GDP growth rates (i.e. $|\beta_N|/|\beta_P| > 1$) in 33 of the 35 countries for carbon and 32 of the 35 countries for sulfur.

To quantify the *average*, cross-country contribution of changing intensity and GDP growth towards changes in carbon and sulfur emissions growth, I estimate the following equations for each of the pooled samples:

$$g^i_{j,t} = c^i_j + \bar{\beta}_j t \text{ for } j = P, N, Y, \tag{8}$$

The above is a regression of growth rates on time for the entire sample of countries which includes country-fixed effects that are captured by a country i specific intercept, c^i_j. Thus, the estimates $\bar{\beta}_j$ for $j = P, N, Y$ represent the *average* rate of decline of emission, intensity and GDP growth rates in the entire sample of countries over a particular period for a particular pollutant. The results for the baseline samples are presented in the top rows of Table 3(a) and 3(b). On average, the growth rate of CO_2 and SO_2 emissions fell by 4.98×10^{-2} and 9.49×10^{-2} percentage points per year respectively for the sample. The average rate of decline of intensity growth was 5.74×10^{-2} percentage points per year for carbon and 10.24×10^{-2} percentage points per year for sulfur whilst the growth rate of GDP for the sample *increased* by 0.76×10^{-2} percentage points per year. The average change in the rate of growth of intensity was thus 7.55 ($\approx 5.74/0.76$) times larger for carbon and 13.47 ($\approx 10.24/0.76$) times larger for sulfur than the change in the rate of GDP growth. Finally, the decline in intensity growth rates accounted for 115% of the decline in emissions growth rates for carbon and 108% for sulfur. The corresponding changes in GDP growth rates accounted for -15% of the decline for carbon and -8% of the decline for sulfur. Thus, on average and over the entire sample period, changes in emission intensity growth rates accounted for more than the entire decline in emission growth rates for both pollutants, whilst changes in GDP growth rates actually contributed to *increasing* rates of emission growth.

Finally, since the change of growth rates may potentially be non-linear over time, in the remaining rows of Table 3(a) and 3(b) I repeat the above exercise whilst considering successively more recent data. The largest contribution of falling GDP growth rates towards falling emission growth rates occurs in the post-Second World War period for both sulfur and carbon. Even then however, declining GDP growth rates contributed only 31% and 22% to the decline in emission

(a) CO_2

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-4.98***	-5.74***	0.76***	1.15	-0.15
	(0.24) 0.11 3832	(0.21) 0.16 3832	(0.07) 0.03 3832		
>1830	-4.94***	-5.70***	0.75***	1.15	-0.15
	(0.24) 0.10 3822	(0.22) 0.16 3822	(0.07) 0.03 3822		
>1850	-4.65***	-5.45***	0.80***	1.17	-0.17
	(0.25) 0.09 3741	(0.22) 0.14 3741	(0.08) 0.03 3741		
>1870	-4.40***	-5.23***	0.84***	1.19	-0.19
	(0.28) 0.07 3540	(0.25) 0.11 3540	(0.09) 0.03 3540		
>1890	-3.98***	-4.78***	0.80***	1.20	-0.20
	(0.35) 0.04 3187	(0.31) 0.07 3187	(0.11) 0.02 3187		
>1910	-3.15***	-4.00***	0.85***	1.27	-0.27
	(0.47) 0.02 2798	(0.42) 0.03 2798	(0.15) 0.01 2798		
>1930	-6.28***	-6.02***	-0.26	0.96	0.04
	(0.65) 0.04 2351	(0.59) 0.04 2351	(0.20) 0.00 2351		
>1950	-17.21***	-11.93***	-5.28***	0.69	0.31
	(0.85) 0.19 1842	(0.81) 0.11 1842	(0.23) 0.23 1842		
>1970	-8.00***	-4.57***	-3.42***	0.57	0.43
	(0.47) 0.20 1191	(0.38) 0.11 1191	(0.36) 0.07 1191		
>1990	-8.81***	-9.87***	1.05	1.12	-0.12
	(1.17) 0.11 511	(0.98) 0.18 511	(0.76) 0.00 511		

*** p<0.01, ** p<0.05, * p<0.1

(b) SO_2

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-9.49***	-10.24***	0.76***	1.08	-0.08
	(0.33) 0.17 3944	(0.32) 0.21 3944	(0.08) 0.02 3944		
>1870	-8.89***	-9.82***	0.93***	1.10	-0.10
	(0.32) 0.18 3702	(0.30) 0.23 3702	(0.09) 0.03 3702		
>1890	-10.40***	-11.38***	0.99***	1.09	-0.09
	(0.40) 0.17 3296	(0.37) 0.22 3296	(0.11) 0.02 3296		
>1910	-10.52***	-11.62***	1.10***	1.10	-0.10
	(0.54) 0.12 2847	(0.50) 0.16 2847	(0.16) 0.02 2847		
>1930	-16.15***	-16.06***	-0.09	0.99	0.01
	(0.77) 0.16 2352	(0.72) 0.18 2352	(0.22) 0.00 2352		
>1950	-27.30***	-21.40***	-5.90***	0.78	0.22
	(0.88) 0.35 1802	(0.86) 0.26 1802	(0.26) 0.23 1802		
>1970	-29.82***	-24.88***	-4.94***	0.83	0.17
	(1.53) 0.26 1102	(1.54) 0.20 1102	(0.42) 0.11 1102		
>1990	-46.50***	-46.97***	0.47	1.01	-0.01
	(7.94) 0.09 402	(7.93) 0.09 402	(1.03) 0.00 402		

*** p<0.01, ** p<0.05, * p<0.1

Table 3: Average change of emission, GDP and emission intensity growth rates ($\times 10^4$) for baseline samples over different periods. Standard errors, R^2 and sample size underneath estimates.

growth rates of carbon and sulfur respectively, whereas declining emission intensity growth rates contributed 69% and 78% respectively. Furthermore, in the period since the 1990's, declining emission intensity growth rates have again accounted for more than a hundred percent of the decline in emission growth rates, whilst changes in GDP growth have reverted to contributing to *rising* emission growth rates.

Robustness In the Appendix, I carry out a number of robustness exercises to the above. First, Figure 4 showed that emission intensities exhibit a hump shape pattern with rising income. This suggests that income can serve as another dimension along which changes in intensity and GDP growth rates could be compared. I repeat the analysis of Tables 2 and 3 along the income dimension and find results that are quantitatively and qualitatively very similar to the baseline. Second, in the above I considered the growth rates of *total* GDP and *total* emissions. In the Appendix, I repeat this exercise in terms of per-capita values and find that all previous results go through. Third, in the baseline I considered only a sample of 35 countries. In the Appendix, using the same data sources, I expand this sample to 149 countries for carbon and 124 countries for sulfur, and show that all results go through. Finally, to avoid the pitfalls of historical GDP and emissions data, to ensure a balanced panel and to consider the same data as Brock and Taylor (2010), I repeat the exercise using Penn World Table and World Development Indicator data. In particular, I form a balanced panel of 94 countries for the years 1960-1998. Once more, all previous results go through in this new sample of data.

5 Structural Transformation: A possible explanation

The primary purpose of this paper is to establish the relative importance of intensity growth rates versus GDP growth rates in determining the EKC rather than to provide a structural model of the phenomenon.[9] Nonetheless, in this section I describe a very simple, micro-founded model of structural transformation that can go some way in accounting for the facts observed in the data.[10] I show how structural transformation - the shift of an economy away from agriculture towards industry and services - in conjunction with exogenous technological progress in abatement can generate a hump-shaped intensity and therefore falling intensity growth rates.

Consumer's Problem On the demand side, the model consists of a utility-maximizing representative consumer who, at each point in time, t, inelastically supplies a unit of labor in exchange

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[9] For a paper that does this in more detail, see Stefanski (2010).

[10] Grossman and Krueger (1991) and others have argued that structural transformation can play a role in emissions. My contribution is to provide a tractable general equilibrium model of this phenomenon. Finally, notice that I do not argue that structural transformation is the only source of the inverted-U.

for wage income, w_t.[11] This income is then used by the consumer to purchase two consumption goods: an agricultural good, a_t , and a non-agricultural good (industry-service composite), c_t. The consumer has preferences over consumption goods given by the following:

$$\sum_{t=0}^{\infty} \beta^t U(a_t, c_t), \tag{9}$$

where $0 < \beta < 1$, is the discount factor. The period utility function, $U(a_t, c_t)$, adopted from Gollin et al. (2002), is of the Stone-Geary type and is chosen to generate a structural transformation:

$$U(a_t, c_t) = \begin{cases} \bar{a} + u(c_t) & \text{if } a_t > \bar{a} \\ a_t & \text{if } a_t \leq \bar{a}. \end{cases} \tag{10}$$

A consumer that has low income cares only about agricultural consumption, whilst a high income consumer becomes satiated with agricultural products when $a_t = \bar{a}$ and devotes the remainder of their income to non-agriculture. The assumption on $u(c_t)$ are the same as in a standard one-sector model: it is assumed to be continuous, twice continuously differentiable, strictly increasing, strictly concave and to satisfy the Inada conditions.[12]

Since no dynamic decisions are made in the model, the consumer faces a sequence of static problems which consist of solving for the optimal allocation of income between agricultural and non-agricultural goods at each point in time given by:

$$\max U(a_t, c_t) \tag{11}$$

$$\text{s.t. } p_t^a a_t + p_t^c c_t = w_t,$$

where, p_t^a is the price of agricultural products and p_t^c is the price of non-agriculture.

Firms' Problems The agricultural and non-agricultural firms hire labor from the consumer and use it to produce final goods, A_t and C_t, which are then sold to the consumer. Firms hire labor to maximize profits with their production functions given by:

$$A_t = g^t B L_{A,t} \text{ and } C_t = g^t B L_{C,t}. \tag{12}$$

In the above equations, I assume for simplicity that labor productivity in both sectors grows at the same exogenous rate, g. Also, for simplicity, labor productivity levels in both sectors at $t = 0$ are assumed to be B.[13]

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[11] It is trivial to extend this setup to include exogenous population growth. Without loss of generality I abstract from it for simplicity.

[12] The reason for adopting this simple type of preferences is analytic tractability. The model is easily extended to a more sophisticated function.

[13] Notice that I assume that there is no capital in the economy. This is assumed for simplicity and without loss of generality. Appendix 7.7 adds capital, and shows that qualitatively all results go through

Pollution To maintain the extreme simplicity of the model, assume that agricultural production emits no pollution, whilst production of non-agriculture emits $\Omega_t = 1/g_A^t$ units of production:

$$P_t = \Omega_t c_t. \tag{13}$$

One justification of this assumption is that agriculture in poorer countries (where it is often the dominant sector in an economy) uses predominantly clean energy like fuelwood or muscle power, whilst non-agriculture tends to use dirtier energy, like coal.[14] Like Brock and Taylor (2010), I am thus assuming that there is an exogenous rate of technological progress in abatement given by, g_A^t. Unlike their paper, to maintain simplicity, I abstract from spending on abatement. This is not crucial to the result and is easily relaxed by adding utility cost of pollution and the ability for agents to choose the extent of abatement.

Market Clearing Finally, the goods and labor market clearing conditions are given by:

$$a_t = A_t \text{ and } c_t = C_t \text{ and } L_{A,t} + L_{C,t} = 1. \tag{14}$$

Solution Due to the simple nature of preferences, $a_t = A_t = \bar{a}$, employment in agriculture falls at the rate g, and is given by: $L_{A,t} = \frac{\bar{a}}{Bg^t}$. Thus, given $\bar{a}$, the aggregate level of productivity in the economy, B, determines the initial employment share in agriculture. It follows from labor market clearing conditions, that employment in non-agriculture is given by, $L_{C,t} = 1 - \frac{\bar{a}}{Bg^t}$, which rises over time. Since both sectors have the same exogenous productivity growth rate, total output - in period-zero prices - is given by, $Y_t = \frac{1}{B}(\bar{a} + c_t) = g^t$.[15] As such, the following describes the time path of total emissions:

$$P_t = \frac{c_t}{g_A^t} = B\left(\frac{g}{g_A}\right)^t L_{C,t} \tag{15}$$

and aggregate emission intensity:

$$N_t = \frac{P_t}{Y_t} = \frac{P_t}{g^t} = B\left(\frac{1}{g_A}\right)^t L_{C,t}. \tag{16}$$

Taking log-differences of the above equation provides a decomposition of the growth rate of emission intensity into two effects, first described by Grossman and Krueger (1991) - the technique effect and the composition effect. The technique effect, captured by $\frac{1}{g_A}$, measures how improvements in technology influence pollution intensity over time. This is the effect that operates in Brock and Taylor (2010): improvements in abatement technology can result in

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[14] Renewable combustibles do not release new CO_2 into the biosphere, whilst burning fossil fuels releases CO_2 locked under the ground into the biosphere. See Stefanski (2010) for details.

[15] I obtain this result by normalizing the wage rate in each period to one.

falling emission intensity. The composition effect, captured by changes in the growth rates of non-agricultural employment, measures how changes in the structure of the economy influence pollution intensity over time. As the economy shifts away from agriculture, the share of (dirty) non-agriculture in value added rises and therefore, this effect is initially strictly positive. If it is large enough, it can outweigh the technique effect, resulting in rising emission intensity. As the economy becomes dominated by non-agriculture, the rate at which the share of non-agriculture in employment increases goes to zero.[16] Thus, over time, the technique effect dominates and emission intensities fall. Depending on parameters (as in the original Green Solow model), this setup can generate a hump-shaped emission intensity curve and hence emission intensity growth rates that fall from above to below zero and an EKC-type profile for emissions.

To see the above, define $t = 0$ as the time when structural transformation starts by assuming that $B = \bar{a}$, which we normalize to one for simplicity. Since the economy is dominated by non-polluting agriculture and $L_{C,0} = 0$, initially emission intensity and total emissions are zero. The long run path of emissions (i.e. emissions as $t \to \infty$) is determined by the ratio g/g_A. If abatement technology is growing at a fast enough rate (i.e. $g/g_A < 1$), emissions tend to zero in the long run. Since for any positive and finite t, $P_t > 0$, we obtain an EKC, which peaks at $t^*_P = \frac{\log\left(\frac{\log(g_A)}{\log(g_A)-\log(g)}\right)}{\log(g)}$. If abatement technology grows at a slower rate than labor productivity (i.e. $g/g_A > 1$), then pollution will rise indefinitely. Thus, in this framework, the falling emissions of the second half of the EKC are driven by the same forces as in the Green Solow model. Rising emissions however, comes from GDP growth and a changing structure of the economy.

Notice that, independent of the existence of the EKC, as long as there is some technological progress in abatement (i.e. $g_A > 1$), pollution intensity will always go to zero in the long run. Since for any positive and finite t, $N_t > 0$, we will always observe a hump shape for emission intensities, even if we do not observe this shape for the EKC. This peak will occur at $t^*_N = \frac{\log\left(1+\frac{\log(g)}{\log(g_A)}\right)}{\log(g)}$. Finally, notice, that if the EKC *does* peak, then it will do so after the emission intensity curve has peaked (i.e. $t^*_P > t^*_N$). Thus, this simple model provides a neat justification of why we observe hump-shaped emission *intensities* for a wide array of pollutants, but hump-shaped emissions only for some pollutants: improvements in abatement technology (or at least factors that look like technology in the data) vary across pollutant types resulting in EKC's for some pollutants but not for others. However, as long as there is some technological progress in abatement we will always observe a hump shape intensity.

Finally, consider the following numerical example. Suppose that $g = 1.02$ and $g_A = 1.026$. Figure 5(a) shows the hump-shaped emissions and emission intensities that result. Figure 5(b) shows how, in this framework, the EKC is being driven by declining intensity growth rates.

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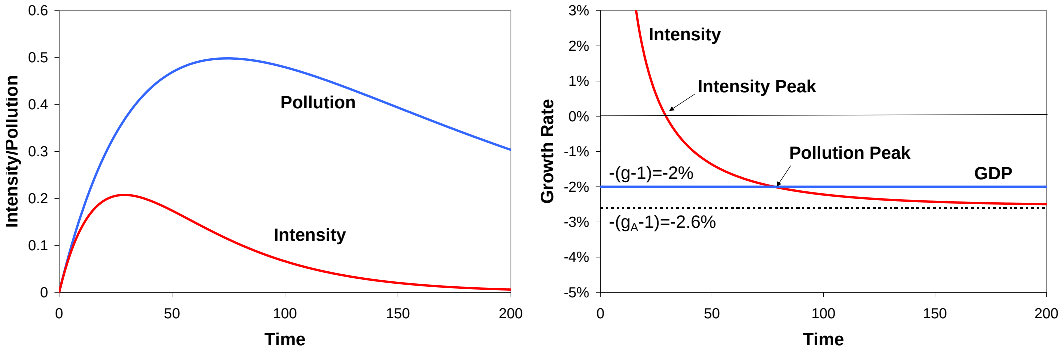
[16] That is, the share of non-agriculture converges smoothly to 1.



(a) Emissions and Intensity (b) Emissions and Intensity Growth Rates

Figure 5: Emissions and Intensity: Levels and Growth Rates.

Intensity peaks when intensity growth rates fall to zero, and emission peaks when intensity growth rates are declining fast enough to outweigh the technological progress in production.

6 Conclusion

Brock and Taylor (2010) provide a valuable contribution to the study of emissions associated with economic activity by placing the theory within the context of the well understood Solow growth model. However, despite the elegance of this approach, a Green Solow model is not necessarily the right framework to think about the emissions of an economy over time. As this paper shows, falling GDP growth rates caused by convergence are not the key driver of emission dynamics. Rather, changes in emission intensity growth rates are key. Any model that wishes to generate an EKC, must concentrate on explaining falling emission intensity growth rates and in particular the hump-shaped emission intensity that is followed by many pollutants. I suggest structural transformation as one (but certainly not the only) such possible mechanism that can go some way to matching the data, and provide a simple framework where a hump-shaped emission intensity curve and a hump-shaped EKC can arise from the changing structure of an economy.

7 Appendix

7.1 USA Data

Ratio	PM10	CO2	CO	NO	SO2	VOC
Q2/Q1	4.44	2.24	0.60	1.42	3.47	1.04
Q3/Q2	0.65	2.41	0.79	2.72	3.36	1.27
Q4/Q1	37.05	16.55	11.43	6.09	4.06	8.53

Table 4: The ratio between the change in intensity of absolute growth rates and the changes in GDP of growth rates between quartiles of the 1948-1998 US data.

Table 4 provides a robustness test of Table 1 in the main body of the paper. I divide the 1948-1998 US pollution intensity data into quartiles, and calculate the average growth rates of pollution intensity and GDP in each quartile and for each pollutant. I then calculate the ratio $R = \frac{|g^N_{t+1} - g^N_t|}{|g^Y_{t+1} - g^Y_t|}$ which describes the relative size of of the change in pollution intensity growth rates with respect to GDP growth rates between two periods. For most quartiles and for most pollutants, the magnitude of the change in pollution intensity growth rates were significantly larger than changes in GDP.

7.2 Baseline International Data

Emissions of CO_2 are measured in (metric) tons of carbon and the data comes from Andres et al. (1999) who make use of historical energy statistics and estimate fossil fuel CO_2 emissions from 1751 to the present for a wide selection of countries. In this exercise, they obtain historical coal, brown coal, peat, and crude oil production data by nation and year for the period 1751-1950 from Etemad et al. (1991) and fossil fuel trade data over this period from Mitchell(1983, 1992, 1993, 1995).[17] This production and trade data is used to calculate fossil fuel consumption over the 1751-1950 period. Carbon dioxide emissions are imputed following the method first developed by Marland and Rotty (1984) and Boden et al. (1995). The 1950-2007 CO_2 emission estimates reported by Andres et al. (1999) are derived primarily from energy consumption statistics published by the United Nations (2006) using the methods of Marland and Rotty (1984). The data is now maintained and updated by the Carbon Dioxide Information Analysis Center.[18] Lefohn et al. (1999) perform a similar exercise for emissions of sulfur for the years 1850-1990 for a wide selection of countries. In all cases, sulfur emission estimates for each country are based on the production, percent sulfur, and sulfur retention information associated

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[17] Mitchell's work tabulates solid and liquid fuel imports and exports by nation and year.

[18] The data is available for download at http://cdiac.ornl.gov/trends/emis/overview.html.

	Year	GDP per capita		Intensity	
		ave	max/min	ave	max/min
Australia	1860 - 2005	8276	9	192	11
Austria	1870 - 2005	6789	12	241	5
Belgium	1846 - 2005	6837	13	402	5
Brazil	1901 - 2005	2579	8	67	2
Canada	1870 - 2005	8275	14	345	16
China	1950 - 2005	1575	11	285	8
Denmark	1843 - 2005	7198	16	163	14
Finland	1860 - 2005	5774	24	95	27
France	1820 - 2005	5763	18	196	19
Germany	1850 - 2005	6333	14	382	8
Greece	1913 - 2005	5301	12	98	21
Hungary	1946 - 2005	5217	5	295	2
India	1884 - 2005	862	4	85	42
Indonesia	1891 - 2005	1382	6	54	115
Iran	1951 - 2005	3797	4	220	42
Ireland	1924 - 2005	7584	10	241	3
Italy	1861 - 2005	5908	13	79	26
Japan	1875 - 2005	6053	27	146	18
Korea, Rep.	1946 - 2005	5432	25	151	42
Malaysia	1970 - 2005	5206	4	182	2
Mexico	1915 - 2005	3821	5	128	4
Netherlands	1846 - 2005	7166	10	192	3
New Zealand	1878 - 2005	8208	5	148	4
Norway	1835 - 2005	6116	32	145	79
Poland	1950 - 2005	4991	4	505	2
Portugal	1870 - 2005	3869	15	87	9
Saudi Arabia	1957 - 2005	8336	4	302	156
Spain	1850 - 2005	4253	17	96	32
Sweden	1839 - 2005	6399	26	136	89
Switzerland	1858 - 2005	9061	12	84	15
Thailand	1950 - 2005	3127	9	82	12
Turkey	1923 - 2005	3166	9	93	3
USSR	1928 - 2005	4211	5	422	4
UK	1830 - 2005	6913	13	445	6
US	1870 - 2005	10594	13	443	4

35 Large Emitters, CO_2

Table 5: Summary statistics for CO_2 for 35 large emitters.

	Year	GDP per capita		Intensity	
		ave	max/min	ave	max/min
Australia	1850 - 2002	7605	10	3.35	5
Austria	1870 - 2002	6454	11	4.36	124
Belgium	1850 - 2002	6678	11	4.82	27
Brazil	1870 - 2000	2026	8	0.82	37
Canada	1870 - 2002	7922	13	17.13	23
China	1950 - 2003	1434	9	4.58	7
Denmark	1850 - 2002	7135	14	2.08	102
Finland	1860 - 2002	5444	22	2.03	73
France	1850 - 2002	6328	13	2.14	18
Germany	1850 - 2001	5993	14	6.50	132
Greece	1913 - 2002	5003	10	1.29	30
Hungary	1946 - 2002	5042	4	13.51	9
India	1884 - 2000	806	3	1.25	12
Indonesia	1891 - 2000	1282	6	0.37	152
Iran	1950 - 2000	3618	4	4.24	7
Ireland	1921 - 2002	6744	9	3.21	7
Italy	1861 - 2002	5625	13	1.08	660
Japan	1870 - 2002	5504	29	2.01	58
Korea, Rep.	1947 - 2000	4518	20	2.08	42
Malaysia	1947 - 2000	3344	7	3.71	18
Mexico	1900 - 2003	3430	5	3.41	3
Netherlands	1850 - 2002	6992	9	2.21	34
New Zealand	1870 - 2002	7712	5	2.11	8
Norway	1850 - 2002	6222	27	1.93	50
Poland	1950 - 2002	4810	3	8.35	4
Portugal	1865 - 2002	3542	15	1.07	6
Saudi Arabia	1950 - 2000	7613	6	5.24	14
Spain	1850 - 2002	3991	15	3.35	6
Sweden	1850 - 2002	6479	21	2.59	58
Switzerland	1852 - 2002	8490	15	0.91	90
Thailand	1950 - 2000	2729	8	0.92	287
Turkey	1923 - 2000	2946	8	1.80	3
USSR	1928 - 2000	4124	5	8.00	4
UK	1850 - 2002	7262	9	7.11	30
US	1870 - 2003	10301	12	8.33	21

35 Large Emitters, SO_2

Table 6: Summary statistics for SO_2 for 35 large emitters.

with that country's activities.[19] Stern (2005) updates this database and extends it for the years 1991 to 2000 (and for some countries until 2003) using observed data when it is available.

The above sources provide the best long run data available. The above emissions data however are *constructed* and depend on estimates of fuel use, technology and trade in the distant past and on other assumptions. The authors of both data sets perform checks with directly measured contemporary data and demonstrate that their estimates overlap well. Having said that, the limitations of this data should be kept in mind when analyzing estimates.

Real GDP and real GDP per capita are expressed in 1990 Geary-Khamis dollars and the data comes from Maddison (2007) for the years 1820-2005. Both emissions and GDP data is smoothed using an HP filter, with smoothing parameter $\lambda = 100$. Importantly, we have checked that this smoothing procedure in no way drives the results (results available on request).

Tables 5 and 6 provide summary statistics for the data. Notice that both data sets cover long periods of time and 35 countries at different income levels. The appealing aspect of the samples is that they provide much cross-country and within country variation - both for emission intensities and GDP per capita. Finally, in the above data I treat the former Soviet Union as one region as data is available only for the USSR before 1991. Here the USSR consists of: Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.

7.3 Income Dimension

Figure 6(a) and 6(b) illustrate how GDP and emission intensity growth rates change in the panel of 35 large emitters with income. The relatively flat lines show the decile averages of GDP growth rates versus GDP per capita income for the panel. The falling lines plot the decile averages of carbon and sulfur dioxide intensity growth rates versus GDP per capita income for the same panel of data. GDP growth rates remain fairly constant as countries grow richer. Growth rates of sulfur and carbon dioxide intensities, however, decline very steeply with income.[20] Table 7, shows the estimates of the slope coefficients from the following regressions:

$$g_{j,t} = c_j + \beta_j \log(y_t) \text{ for } j = P, N, Y, \tag{17}$$

where y_t is GDP per capita and β_j is the average rate of change of growth over GDP per capita. Results are similar to the time dimension. Emission growth rates and emission intensity growth rates decline for almost all countries in both carbon and sulfur. Furthermore, the magnitude of

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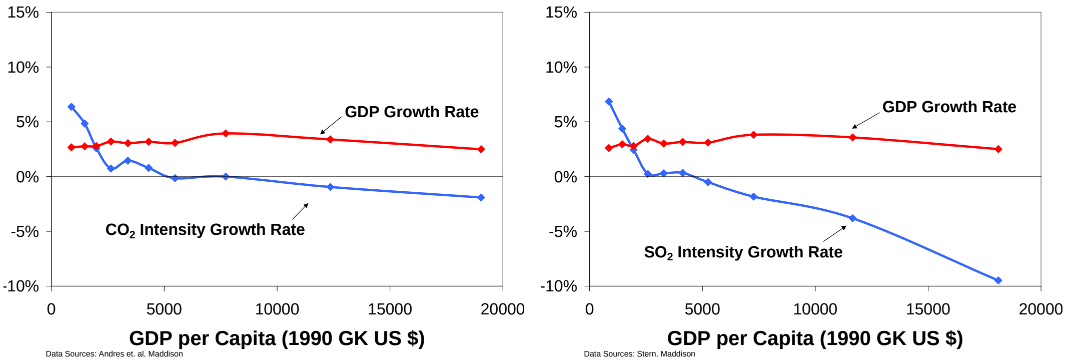
[19] This differs from carbon emissions estimates, in that the retention rate of carbon dioxide is negligible, whilst that of sulfur is not - i.e. sulfur can be scrubbed from fuels before they are burnt, whilst carbon dioxide is an unavoidable byproduct of the burning process.

[20] GDP growth rates are actually slightly hump-shaped with income. This is in line with evidence presented by Echevarria (1997) and others, who documents a hump shape of GDP per capita growth rates with income.



(a) CO_2 (b) SO_2

Figure 6: GDP and emission intensity growth rates at different levels of GDP/capita (baseline).

the change in emission intensity growth rates dominates changes in GDP growth rate for almost all countries in both samples.

To quantify the *average*, cross-country contribution of changing intensity and GDP growth towards changes in carbon and sulfur emissions growth, I estimate the following equations for each of the pooled samples:

$$g^i_{j,t} = c^i_j + \bar{\beta}_j \log(y^i_t) \text{ for } j = P, N, Y, \tag{18}$$

where c^i_j is a country fixed effect and $\bar{\beta}_j$ represents the *average* rate of decline of growth with income per capita in the entire sample of countries. The results are presented in the top rows of Table 8(a) and 8(b). On average, a one percent increase in GDP per capita is associated with a decline in the growth rate of CO_2 and SO_2 emissions of -261.08×10^{-2} and -521.16×10^{-2} percentage points respectively. The average rate of decline of intensity growth was 296.32×10^{-2} percentage points for carbon and 561.01×10^{-2} percentage points for sulfur, whilst the growth rate of GDP for the sample *increased* by 35.24×10^{-2} percentage points in the carbon sample and by 39.85×10^{-2} percentage points in the sulfur sample. The average change in the rate of growth of intensity with income was thus 8.41 ($\approx 296.32/35.24$) times larger for carbon and 14.08 ($\approx 561.01/39.85$) times larger for sulfur than the change in the rate of GDP growth. The decline in intensity growth rates accounted for 113% of the decline in emissions growth rates for carbon and 108% for sulfur. The corresponding changes in GDP growth rates accounted for -13% of the decline for carbon and -8% of the decline for sulfur. Finally, restricting the sample to successively richer deciles of the data, the remaining rows of Table 8(a) and 8(b) demonstrate that intensity is important at driving changing emissions growth rates in both rich and poor countries. In the carbon data, its role declines with income, whereas in the sulfur data the role of changing intensity growth is smallest in middle income countries.

	CO2	Int	GDP	SO2	Int	GDP
Australia	-283.65***	-297.65***	14.00	-123.15**	-40.53	-82.62***
	(32.50) 0.35	(28.95) 0.43	(17.68) 0.00	(49.55) 0.04	(60.14) 0.00	(28.56) 0.05
Austria	0.51	-74.83	75.34***	-505.22***	-588.71***	83.49***
	(56.57) 0.00	(48.73) 0.02	(21.88) 0.08	(63.04) 0.33	(49.37) 0.52	(23.01) 0.09
Belgium	-177.20***	-203.24***	26.04*	-508.57***	-545.45***	36.88**
	(24.13) 0.26	(13.97) 0.57	(14.46) 0.02	(40.37) 0.51	(30.32) 0.68	(15.71) 0.04
Brazil	-21.30	-23.04	1.73	-180.31***	-266.00***	85.69***
	(42.47) 0.00	(33.28) 0.01	(22.26) 0.00	(62.79) 0.06	(63.62) 0.12	(19.82) 0.13
Canada	-392.54***	-401.66***	9.11	-503.47***	-517.07***	13.60
	(37.35) 0.45	(34.50) 0.51	(15.99) 0.00	(22.24) 0.80	(15.65) 0.89	(16.67) 0.01
China	-518.65***	-731.50***	212.85***	-878.51***	-1062.57***	184.06***
	(186.07) 0.13	(175.95) 0.25	(19.90) 0.68	(202.07) 0.27	(190.66) 0.38	(24.29) 0.53
Denmark	-280.80***	-291.44***	10.63	-765.42***	-785.89***	20.47**
	(19.67) 0.56	(16.71) 0.66	(8.21) 0.01	(90.44) 0.32	(87.24) 0.35	(9.04) 0.03
Finland	-110.40**	-143.93***	33.53***	-486.93***	-521.42***	34.49***
	(50.23) 0.03	(42.77) 0.07	(9.38) 0.08	(53.28) 0.37	(47.53) 0.46	(9.82) 0.08
France	-224.52***	-299.02***	74.50***	-412.90***	-505.78***	92.88***
	(22.55) 0.35	(14.18) 0.71	(15.22) 0.12	(34.87) 0.48	(22.05) 0.78	(20.36) 0.12
Germany	-6018.18***	-5655.83***	-362.33***	-757.86***	-781.36***	23.50
	(627.19) 0.88	(642.74) 0.86	(21.63) 0.96	(78.75) 0.38	(74.80) 0.42	(21.70) 0.01
Greece	-310.62**	-322.61***	11.99	-298.10*	-300.25**	2.14
	(147.88) 0.05	(118.61) 0.08	(42.02) 0.00	(160.47) 0.04	(142.68) 0.05	(44.84) 0.00
Hungary	-1296.19***	-803.95***	-492.24***	-1710.67***	-1109.53***	-601.14***
	(74.07) 0.84	(42.15) 0.87	(62.18) 0.52	(94.73) 0.86	(99.64) 0.70	(52.35) 0.71
India	-100.46	-637.57***	537.11***	-106.25	-669.22***	562.97***
	(77.42) 0.01	(66.55) 0.44	(27.91) 0.76	(70.82) 0.02	(55.80) 0.56	(35.99) 0.68
Indonesia	-318.03***	-332.16***	14.13	-533.47**	-785.94***	252.47***
	(99.42) 0.16	(84.36) 0.22	(43.87) 0.00	(218.70) 0.05	(212.78) 0.11	(37.08) 0.30
Iran	-3531.29***	-3150.73***	-380.56***	111.87	428.43***	-316.56**
	(658.77) 0.36	(678.78) 0.29	(115.13) 0.17	(105.92) 0.02	(102.83) 0.27	(126.92) 0.12
Ireland	27.09	-246.92***	274.01***	-368.09***	-674.21***	306.12***
	(31.60) 0.01	(24.41) 0.56	(15.07) 0.81	(69.65) 0.26	(64.06) 0.58	(14.19) 0.86
Italy	-168.54***	-225.82***	57.28***	-709.48***	-775.80***	66.32***
	(41.78) 0.10	(34.09) 0.24	(17.19) 0.07	(221.95) 0.07	(219.99) 0.08	(17.78) 0.09
Japan	-216.87***	-253.47***	36.59*	-514.93***	-564.78***	49.85**
	(31.99) 0.26	(23.15) 0.48	(21.97) 0.02	(50.62) 0.44	(49.52) 0.50	(21.75) 0.04
Korea Rep.	-892.61***	-858.81***	-33.80	-1435.43***	-1432.48***	-2.96
	(162.03) 0.35	(164.25) 0.32	(20.81) 0.04	(384.24) 0.22	(383.75) 0.22	(23.74) 0.00
Malaysia	-6.73	258.14***	-264.87***	332.03***	226.08***	105.95***
	(73.55) 0.00	(60.20) 0.36	(38.48) 0.59	(46.16) 0.50	(35.69) 0.44	(27.15) 0.23
Mexico	-183.82***	-253.46***	69.65*	-49.43	-154.44***	105.01***
	(64.83) 0.08	(54.78) 0.20	(41.50) 0.03	(49.68) 0.01	(54.29) 0.07	(36.82) 0.08
Netherlands	-67.72**	-137.49***	69.78***	-490.73***	-573.21***	82.48***
	(27.01) 0.04	(15.76) 0.33	(18.09) 0.09	(47.02) 0.42	(33.07) 0.67	(19.58) 0.11
New Zealand	-211.68***	-203.38***	-8.30	-422.82***	-320.23***	-102.58***
	(55.45) 0.10	(51.59) 0.11	(19.79) 0.00	(42.53) 0.43	(43.07) 0.30	(29.01) 0.09
Norway	-257.26***	-304.44***	47.18***	-575.15***	-626.54***	51.39***
	(31.68) 0.28	(30.94) 0.37	(5.89) 0.28	(39.53) 0.59	(35.86) 0.67	(6.75) 0.28
Poland	-746.11***	-504.79***	-241.32***	-1296.46***	-950.76***	-345.70***
	(86.05) 0.59	(80.33) 0.43	(75.46) 0.16	(173.69) 0.53	(190.61) 0.33	(76.91) 0.29
Portugal	-46.56	-128.51***	81.94***	-47.62*	-150.46***	102.84***
	(49.30) 0.01	(49.10) 0.05	(13.18) 0.23	(26.51) 0.02	(23.13) 0.24	(12.45) 0.34
Saudi Arabia	-5389.82***	-4871.34***	-518.49***	193.50	453.75***	-260.25**
	(641.61) 0.61	(567.44) 0.62	(174.85) 0.16	(159.57) 0.03	(134.04) 0.19	(103.39) 0.12
Spain	-158.25***	-278.31***	120.07***	-242.77***	-368.58***	125.81***
	(42.61) 0.08	(38.66) 0.25	(17.47) 0.24	(30.29) 0.30	(21.77) 0.66	(18.52) 0.24
Sweden	-390.46***	-402.19***	11.73*	-656.68***	-660.82***	4.14
	(31.41) 0.49	(29.50) 0.53	(6.23) 0.02	(46.83) 0.57	(43.25) 0.61	(7.09) 0.00
Switzerland	-282.44***	-296.57***	14.13	-834.60***	-834.06***	-0.54
	(48.13) 0.19	(46.69) 0.22	(13.61) 0.01	(81.06) 0.42	(75.35) 0.45	(12.57) 0.00
Thailand	-508.43***	-415.79***	-92.65***	-1824.27***	-1766.99***	-57.28**
	(64.20) 0.54	(61.51) 0.46	(24.88) 0.21	(237.43) 0.55	(238.00) 0.54	(29.04) 0.08
Turkey	-159.79***	-88.97***	-70.81**	-168.40***	-98.13**	-70.27**
	(42.16) 0.15	(24.67) 0.14	(31.23) 0.06	(57.33) 0.10	(49.13) 0.05	(34.97) 0.05
USSR	-595.06***	-469.91***	-125.15***	-981.42***	-728.64***	-252.78***
	(80.60) 0.47	(56.35) 0.53	(44.03) 0.12	(115.16) 0.51	(66.09) 0.64	(80.73) 0.12
UK	-170.97***	-192.32***	21.35**	-588.53***	-623.31***	34.77***
	(10.29) 0.62	(8.17) 0.76	(8.59) 0.03	(36.85) 0.63	(38.18) 0.64	(11.32) 0.06
US	-238.87***	-206.58***	-32.29**	-389.60***	-358.32***	-31.28**
	(21.84) 0.47	(15.24) 0.58	(14.48) 0.04	(25.89) 0.63	(16.87) 0.78	(14.94) 0.03

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 7: Estimates of equation (6) by country for Sulfur and Carbon in baseline samples vs. GDP per capita. Standard errors and R^2 underneath estimates. All values multiplied by 10^4 for ease of reading.

(a) CO_2

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-261.08*** (11.95) 0.11 3832	-296.32*** (10.85) 0.16 3832	35.24*** (3.66) 0.02 3832	1.13	-0.13
>1223	-211.45*** (12.14) 0.08 3452	-235.53*** (10.69) 0.12 3452	24.08*** (4.05) 0.01 3452	1.11	-0.11
>1786	-177.51*** (11.60) 0.07 3061	-188.51*** (9.50) 0.12 3061	11.00** (4.70) 0.00 3061	1.06	-0.06
>2354	-180.14*** (12.73) 0.07 2668	-171.33*** (10.32) 0.10 2668	-8.81 (5.41) 0.00 2668	0.95	0.05
>3108	-227.25*** (15.29) 0.09 2281	-201.39*** (12.64) 0.10 2281	-25.85*** (6.44) 0.01 2281	0.89	0.11
>3968	-238.24*** (14.87) 0.12 1887	-179.94*** (10.81) 0.13 1887	-58.30*** (7.67) 0.03 1887	0.76	0.24
>5084	-283.70*** (16.88) 0.16 1489	-168.42*** (12.04) 0.12 1489	-115.27*** (8.87) 0.10 1489	0.59	0.41
>6811	-424.23*** (18.90) 0.32 1101	-238.28*** (13.32) 0.23 1101	-185.96*** (10.70) 0.22 1101	0.56	0.44
>10430	-396.89*** (26.75) 0.24 727	-196.53*** (20.81) 0.12 727	-200.36*** (13.99) 0.23 727	0.50	0.50
>16316	-74.13 (46.51) 0.01 337	-20.53 (45.53) 0.00 337	-53.59*** (19.01) 0.03 337	0.28	0.72

*** p<0.01, ** p<0.05, * p<0.1

(b) SO_2

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-521.16*** (16.74) 0.20 3944	-561.01*** (16.07) 0.24 3944	39.85*** (4.05) 0.02 3944	1.08	-0.08
>1132	-478.66*** (15.54) 0.21 3559	-505.63*** (14.69) 0.25 3559	26.97*** (4.34) 0.01 3559	1.06	-0.06
>1691	-481.14*** (12.81) 0.31 3170	-494.99*** (11.36) 0.38 3170	13.85*** (5.01) 0.00 3170	1.03	-0.03
>2202	-503.75*** (14.77) 0.30 2778	-497.86*** (13.22) 0.34 2778	-5.89 (5.82) 0.00 2778	0.99	0.01
>2897	-591.36*** (17.36) 0.33 2385	-578.48*** (15.43) 0.37 2385	-12.89* (6.79) 0.00 2385	0.98	0.02
>3661	-698.58*** (21.79) 0.35 1989	-655.63*** (19.50) 0.37 1989	-42.95*** (8.05) 0.01 1989	0.94	0.06
>4601	-832.84*** (29.55) 0.34 1590	-742.60*** (27.16) 0.32 1590	-90.23*** (9.36) 0.06 1590	0.89	0.11
>5986	-1077.11*** (43.60) 0.34 1193	-892.05*** (41.67) 0.28 1193	-185.05*** (10.59) 0.21 1193	0.83	0.17
>9019	-1356.84*** (81.70) 0.26 795	-1129.72*** (80.89) 0.20 795	-227.12*** (14.78) 0.23 795	0.83	0.17
>14416	-1289.45*** (249.88) 0.07 398	-1269.22*** (250.01) 0.06 398	-20.24 (19.96) 0.00 398	0.98	0.02

*** p<0.01, ** p<0.05, * p<0.1

Table 8: Average change of emission, GDP and emission intensity growth rates ($\times 10^4$) over the log of GDP per capita for different GDP per capita levels. Standard errors, R^2 and sample size underneath estimates.

(a) CO_2 per capita

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-4.65***	-5.74***	1.09***	1.23	-0.23
	(0.23) 0.09 3832	(0.21) 0.16 3832	(0.07) 0.07 3832		
>1830	-4.61***	-5.70***	1.09***	1.24	-0.24
	(0.24) 0.09 3822	(0.22) 0.16 3822	(0.07) 0.06 3822		
>1850	-4.31***	-5.45***	1.14***	1.26	-0.26
	(0.25) 0.08 3741	(0.22) 0.14 3741	(0.07) 0.06 3741		
>1870	-3.99***	-5.23***	1.24***	1.31	-0.31
	(0.28) 0.06 3540	(0.25) 0.11 3540	(0.08) 0.06 3540		
>1890	-3.56***	-4.78***	1.22***	1.34	-0.34
	(0.35) 0.03 3187	(0.31) 0.07 3187	(0.10) 0.04 3187		
>1910	-2.73***	-4.00***	1.27***	1.47	-0.47
	(0.47) 0.01 2798	(0.42) 0.03 2798	(0.14) 0.03 2798		
>1930	-5.49***	-6.02***	0.53***	1.10	-0.10
	(0.64) 0.03 2351	(0.59) 0.04 2351	(0.19) 0.00 2351		
>1950	-15.29***	-11.93***	-3.36***	0.78	0.22
	(0.85) 0.15 1842	(0.81) 0.11 1842	(0.23) 0.10 1842		
>1970	-5.92***	-4.57***	-1.34***	0.77	0.23
	(0.47) 0.12 1191	(0.38) 0.11 1191	(0.37) 0.01 1191		
>1990	-6.39***	-9.87***	3.48***	1.54	-0.54
	(1.20) 0.06 511	(0.98) 0.18 511	(0.78) 0.04 511		

*** p<0.01, ** p<0.05, * p<0.1

(b) SO_2 per capita

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-9.10***	-10.24***	1.14***	1.13	-0.13
	(0.33) 0.16 3944	(0.32) 0.21 3944	(0.07) 0.06 3944		
>1870	-8.53***	-9.82***	1.28***	1.15	-0.15
	(0.31) 0.17 3702	(0.30) 0.23 3702	(0.08) 0.06 3702		
>1890	-10.10***	-11.38***	1.28***	1.13	-0.13
	(0.40) 0.17 3296	(0.37) 0.22 3296	(0.11) 0.04 3296		
>1910	-10.28***	-11.62***	1.34***	1.13	-0.13
	(0.53) 0.12 2847	(0.50) 0.16 2847	(0.15) 0.03 2847		
>1930	-15.52***	-16.06***	0.54**	1.03	-0.03
	(0.76) 0.15 2352	(0.72) 0.18 2352	(0.21) 0.00 2352		
>1950	-25.54***	-21.40***	-4.14***	0.84	0.16
	(0.87) 0.33 1802	(0.86) 0.26 1802	(0.26) 0.13 1802		
>1970	-27.86***	-24.88***	-2.98***	0.89	0.11
	(1.54) 0.24 1102	(1.54) 0.20 1102	(0.43) 0.04 1102		
>1990	-43.38***	-46.97***	3.59***	1.08	-0.08
	(7.97) 0.08 402	(7.93) 0.09 402	(0.98) 0.04 402		

*** p<0.01, ** p<0.05, * p<0.1

Table 9: Average change of per capita emissions, GDP per capita and emission intensity growth rates ($\times 10^4$) for baseline samples over different periods.Standard errors, R^2 and sample size underneath estimates.

(a) CO_2 per capita vs log of GDP per capita

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-241.59***	-296.32***	54.73***	1.23	-0.23
	(11.87) 0.10 3832	(10.85) 0.16 3832	(3.41) 0.06 3832		
>1223	-190.17***	-235.53***	45.36***	1.24	-0.24
	(12.05) 0.07 3452	(10.69) 0.12 3452	(3.81) 0.04 3452		
>1786	-154.71***	-188.51***	33.80***	1.22	-0.22
	(11.52) 0.06 3061	(9.50) 0.12 3061	(4.44) 0.02 3061		
>2354	-153.55***	-171.33***	17.78***	1.12	-0.12
	(12.57) 0.05 2668	(10.32) 0.10 2668	(5.14) 0.01 2668		
>3108	-197.81***	-201.39***	3.58	1.02	-0.02
	(15.17) 0.07 2281	(12.63) 0.10 2281	(6.21) 0.00 2281		
>3968	-206.69***	-179.94***	-26.75***	0.87	0.13
	(14.68) 0.10 1887	(10.78) 0.13 1887	(7.52) 0.01 1887		
>5084	-246.84***	-168.42***	-78.42***	0.68	0.32
	(16.64) 0.13 1489	(12.04) 0.12 1489	(8.78) 0.05 1489		
>6811	-365.59***	-238.28***	-127.32***	0.65	0.35
	(18.45) 0.27 1101	(13.29) 0.23 1101	(10.42) 0.12 1101		
>10430	-346.06***	-196.53***	-149.53***	0.57	0.43
	(25.13) 0.21 727	(20.60) 0.12 727	(12.94) 0.16 727		
>16316	-54.67	-20.53	-34.14*	0.38	0.62
	(50.51) 0.00 337	(50.42) 0.00 337	(19.31) 0.01 337		

*** p<0.01, ** p<0.05, * p<0.1

(b) SO_2 per capita vs log of GDP per capita

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-501.65***	-561.01***	59.36***	1.12	-0.12
	(16.68) 0.19 3944	(16.07) 0.24 3944	(3.67) 0.06 3944		
>1132	-455.38***	-505.63***	50.26***	1.11	-0.11
	(15.49) 0.20 3559	(14.69) 0.25 3559	(3.97) 0.04 3559		
>1691	-455.60***	-494.99***	39.39***	1.09	-0.09
	(12.70) 0.29 3170	(11.36) 0.38 3170	(4.58) 0.02 3170		
>2202	-472.88***	-497.86***	24.98***	1.05	-0.05
	(14.65) 0.28 2778	(13.22) 0.34 2778	(5.31) 0.01 2778		
>2897	-561.62***	-578.48***	16.86***	1.03	-0.03
	(17.08) 0.32 2385	(15.43) 0.37 2385	(6.37) 0.00 2385		
>3661	-665.87***	-655.63***	-10.23	0.98	0.02
	(21.45) 0.33 1989	(19.50) 0.37 1989	(7.75) 0.00 1989		
>4601	-799.53***	-742.60***	-56.92***	0.93	0.07
	(29.21) 0.33 1590	(27.16) 0.32 1590	(9.13) 0.02 1590		
>5986	-1028.03***	-892.05***	-135.98***	0.87	0.13
	(43.38) 0.33 1193	(41.67) 0.28 1193	(10.37) 0.13 1193		
>9019	-1291.17***	-1129.72***	-161.45***	0.87	0.13
	(82.11) 0.24 795	(80.89) 0.20 795	(14.30) 0.14 795		
>14416	-1279.34***	-1269.22***	-10.12	0.99	0.01
	(250.78) 0.06 398	(250.01) 0.06 398	(18.22) 0.00 398		

*** p<0.01, ** p<0.05, * p<0.1

Table 10: Average change of per capita emission, GDP per capita and emission intensity growth rates ($\times 10^4$) over the log of GDP per capita for different GDP per capita levels. Standard errors, R^2 and sample size underneath estimates.

(a) CO_2 (All Data)

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-8.30***	-8.13***	-0.18**	0.98	0.02
	(0.33) 0.07 8963	(0.30) 0.08 8963	(0.09) 0.00 8963		
>1830	-8.31***	-8.12***	-0.19**	0.98	0.02
	(0.33) 0.07 8953	(0.31) 0.07 8953	(0.09) 0.00 8953		
>1850	-8.35***	-8.12***	-0.23**	0.97	0.03
	(0.35) 0.06 8872	(0.32) 0.07 8872	(0.09) 0.00 8872		
>1870	-8.84***	-8.45***	-0.39***	0.96	0.04
	(0.38) 0.06 8671	(0.35) 0.06 8671	(0.10) 0.00 8671		
>1890	-10.01***	-9.19***	-0.82***	0.92	0.08
	(0.45) 0.06 8318	(0.41) 0.06 8318	(0.12) 0.01 8318		
>1910	-11.10***	-9.79***	-1.30***	0.88	0.12
	(0.53) 0.05 7894	(0.49) 0.05 7894	(0.14) 0.01 7894		
>1930	-15.89***	-13.16***	-2.74***	0.83	0.17
	(0.64) 0.08 7378	(0.59) 0.07 7378	(0.17) 0.03 7378		
>1950	-21.36***	-16.27***	-5.10***	0.76	0.24
	(0.73) 0.12 6745	(0.67) 0.08 6745	(0.20) 0.09 6745		
>1970	-6.38***	-6.18***	-0.20	0.97	0.03
	(0.90) 0.01 4656	(0.81) 0.01 4656	(0.35) 0.00 4656		
>1990	-5.12*	-21.59***	16.47***	4.22	-3.22
	(3.11) 0.00 2167	(2.97) 0.03 2167	(0.84) 0.16 2167		

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

(b) SO_2 (All Data)

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-9.56***	-9.64***	0.08	1.01	-0.01
	(0.41) 0.06 8907	(0.41) 0.06 8907	(0.08) 0.00 8907		
>1870	-9.29***	-9.27***	-0.02	1.00	0.00
	(0.44) 0.05 8665	(0.43) 0.05 8665	(0.09) 0.00 8665		
>1890	-11.09***	-10.64***	-0.45***	0.96	0.04
	(0.52) 0.05 8219	(0.51) 0.05 8219	(0.11) 0.00 8219		
>1910	-11.24***	-10.20***	-1.03***	0.91	0.09
	(0.63) 0.04 7686	(0.62) 0.03 7686	(0.13) 0.01 7686		
>1930	-13.90***	-11.43***	-2.47***	0.82	0.18
	(0.82) 0.04 7001	(0.81) 0.03 7001	(0.16) 0.03 7001		
>1950	-18.65***	-12.94***	-5.71***	0.69	0.31
	(1.07) 0.05 6154	(1.07) 0.02 6154	(0.19) 0.13 6154		
>1970	-19.99***	-15.97***	-4.02***	0.80	0.20
	(1.28) 0.06 3749	(1.28) 0.04 3749	(0.36) 0.03 3749		
>1990	-31.86***	-39.26***	7.40***	1.23	-0.23
	(6.59) 0.02 1296	(6.60) 0.03 1296	(0.88) 0.06 1296		

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 11: Average change of emission, GDP and emission intensity growth rates ($\times 10^4$) for baseline samples over different periods.Standard errors, R^2 and sample size underneath estimates. (All Data)

(a) CO_2 (All Data)

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-302.55***	-330.27***	27.73***	1.09	-0.09
	(17.27) 0.03 8963	(15.77) 0.05 8963	(4.54) 0.00 8963		
>742	-292.09***	-315.60***	23.51***	1.08	-0.08
	(16.66) 0.04 8081	(14.99) 0.05 8081	(4.66) 0.00 8081		
>1049	-267.61***	-286.02***	18.41***	1.07	-0.07
	(17.45) 0.03 7182	(15.64) 0.05 7182	(4.99) 0.00 7182		
>1413	-298.46***	-299.63***	1.17	1.00	0.00
	(18.48) 0.04 6287	(16.80) 0.05 6287	(5.23) 0.00 6287		
>1998	-248.15***	-233.09***	-15.05**	0.94	0.06
	(19.83) 0.03 5372	(17.85) 0.03 5372	(6.02) 0.00 5372		
>2628	-241.84***	-216.13***	-25.71***	0.89	0.11
	(22.92) 0.03 4457	(20.84) 0.02 4457	(6.88) 0.00 4457		
>3429	-216.95***	-178.18***	-38.77***	0.82	0.18
	(25.19) 0.02 3544	(22.61) 0.02 3544	(8.19) 0.01 3544		
>4510	-150.78***	-99.57***	-51.21***	0.66	0.34
	(34.00) 0.01 2635	(30.76) 0.00 2635	(10.65) 0.01 2635		
>6428	-99.72**	-27.16	-72.56***	0.27	0.73
	(47.12) 0.00 1728	(42.63) 0.00 1728	(15.09) 0.01 1728		
>11402	428.75***	293.64**	135.11***	0.68	0.32
	(139.13) 0.01 844	(129.81) 0.01 844	(32.93) 0.02 844		

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

(b) SO_2 (All Data)

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-428.75***	-464.11***	35.36***	1.08	-0.08
	(21.39) 0.04 8907	(21.01) 0.05 8907	(4.14) 0.01 8907		
>726	-435.11***	-467.08***	31.98***	1.07	-0.07
	(21.14) 0.05 8037	(20.73) 0.06 8037	(4.27) 0.01 8037		
>1010	-421.86***	-449.46***	27.60***	1.07	-0.07
	(22.12) 0.05 7156	(21.72) 0.06 7156	(4.53) 0.01 7156		
>1287	-443.22***	-463.24***	20.01***	1.05	-0.05
	(23.69) 0.05 6272	(23.30) 0.06 6272	(4.86) 0.00 6272		
>1751	-429.91***	-442.80***	12.89**	1.03	-0.03
	(25.43) 0.05 5389	(24.93) 0.06 5389	(5.36) 0.00 5389		
>2329	-462.71***	-461.77***	-0.94	1.00	0.00
	(29.85) 0.05 4496	(29.45) 0.05 4496	(6.14) 0.00 4496		
>3027	-493.59***	-482.21***	-11.38	0.98	0.02
	(35.52) 0.05 3607	(35.07) 0.05 3607	(7.34) 0.00 3607		
>3986	-545.01***	-509.16***	-35.85***	0.93	0.07
	(43.96) 0.06 2706	(43.34) 0.05 2706	(9.56) 0.01 2706		
>5517	-752.08***	-654.43***	-97.66***	0.87	0.13
	(51.94) 0.11 1804	(51.78) 0.08 1804	(13.18) 0.03 1804		
>10113	-339.50***	-370.28***	30.77	1.09	-0.09
	(129.80) 0.01 900	(133.29) 0.01 900	(26.04) 0.00 900		

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 12: Average change of emission, GDP and emission intensity growth rates ($\times 10^4$) over the log of GDP per capita for different GDP per capita levels. Standard errors, R^2 and sample size underneath estimates. (All Data)

7.4 Baseline in Per Capita Terms

I repeat the regressions in equations 8 and 18 for the baseline sample of countries in *per capita* terms. That is, I decompose emissions *per capita* into emission intensity and GDP *per capita.* I then examine how changes in growth rates of the latter two terms contribute to changes in the former term. The results versus time and (the log of) GDP per capita for both carbon and sulfur are shown in table 9 and 10 respectively. These tables show that, if anything, the contribution of falling emission intensity growth to falling per capita emission growth is stronger than to *total* emissions growth.

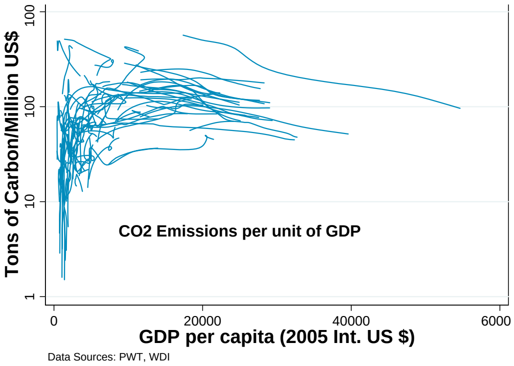
7.5 All Data

For the reasons mentioned in section 3.2, I considered only 35 countries in the baseline sample. The emissions data from Andres et al. (1999) and Lefohn et al. (1999) as well as the GDP data from Maddison (2007) is available for a significantly larger number of countries. I now show the results for regressions (both versus time and the log of GDP per capita) of the entire sample of data. The complete carbon sample contains 8963 observations and 149 countries whilst the sulfur sample contains 8907 observations and 124 countries. The results are shown in tables 11 (versus time) and 12 (versus the log of GDP per capita). Very similar results to those found in the baseline sample hold. In the entire sample, changes in emission intensity growth rates are still overwhelmingly driving changes in emission growth rates. The contribution of emission intensity growth rates is smallest in the post-war period and in middle-income countries - although it almost always dominates the contribution of changing GDP growth rates.

7.6 Contemporary Data

Here I demonstrate that the facts established in the main part of the paper hold using the same international data used by Brock and Taylor (2010). In particular, I use the Penn World Tables and the World Development Indicators database to collect data on carbon emissions, population and GDP, and to construct the same balanced panel of 94 countries for the years 1960-1998. Figure 7 plots emission intensities versus GDP per capita for the above sample of countries. A similar hump-shaped pattern emerges, although - unsurprisingly - due to the larger sample and shorter time period, there is more dispersion in the data.

Table 13(a) shows regression 8 over time for the contemporary data. The decline in intensity growth rates accounts for 65% of the decline in emission growth rates over the entire period and is also dominant in the other subperiods. Table 13(b) shows regression 18 over the log of GDP per capita. The decline in intensity growth rates accounts for 67% of the decline in emission growth rates over the entire sample. Changing intensity growth rates contribute the



Data Sources: PWT, WDI

Figure 7: 94 Emitters: Carbon Dioxide Emission Intensities, 1960-1998 (PWT, WDI data)

least in middle income countries, but still play an important role. Finally, table 14 repeats the above accounting exercises in per capita terms and find that the decline in intensity growth rates accounts for 67% of the decline in emissions growth rates in the time dimension, and 73% in the income dimension with similarly strong results in different sub-samples of the data.

7.7 Capital Accumulation

It is important to note that I do not argue that capital accumulation plays no role in driving emissions. It is easy to extend the baseline model to include capital like in Gollin et al. (2002), and obtain an important role for capital accumulation. However, this channel fails to account for the importance of changing intensity growth rates. If anything, it increases the role of changing GDP growth rates in emissions formation and therefore does not address the main empirical finding of this paper. To see this, consider the following simple extension.

Firms Suppose that the non-agricultural production function is now given by:

$$C_t + I_t = (g^{1-\alpha})^t B L_{C,t}^{1-\alpha} K_t^{\alpha} + \nu L_{C,t}. \tag{19}$$

In the above, K_t is capital and α is the capital share. Furthermore, non-agriculture can now also be used for the production of investment goods. The remaining variables are the same as before. This production function is standard except for the term ν, which is chosen like in Gollin et al. (2002) to allow an economy with no physical capital to accumulate capital. In the numerical experiments, I shall pick ν to be a very small number. The non-agricultural firms now hire labor and rent capital from consumers to maximize profits with their production functions given by the above.

(a) CO_2 (modern) versus time

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-21.65***	-14.00***	-7.64***	0.65	0.35
	(0.65) 0.24 3572	(0.61) 0.13 3572	(0.32) 0.14 3572		
>1968	-12.46***	-6.88***	-5.59***	0.55	0.45
	(0.64) 0.12 2820	(0.62) 0.04 2820	(0.44) 0.06 2820		
>1978	3.40***	2.22**	1.18	0.65	0.35
	(0.93) 0.01 1880	(0.98) 0.00 1880	(0.73) 0.00 1880		
>1988	-4.74***	-5.89***	1.16	1.24	-0.24
	(1.19) 0.02 940	(1.99) 0.01 940	(1.78) 0.00 940		

*** p<0.01, ** p<0.05, * p<0.1

(b) CO_2 (modern) versus log of GDP per capita

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-635.60***	-426.03***	-209.57***	0.67	0.33
	(28.13) 0.13 3572	(25.44) 0.08 3572	(13.63) 0.06 3572		
>1078	-684.49***	-400.14***	-284.35***	0.58	0.42
	(24.79) 0.20 3221	(22.06) 0.10 3221	(13.16) 0.13 3221		
>1478	-679.42***	-373.10***	-306.32***	0.55	0.45
	(23.91) 0.23 2869	(21.26) 0.10 2869	(13.73) 0.15 2869		
>2029	-684.47***	-340.97***	-343.49***	0.50	0.50
	(23.62) 0.26 2509	(20.20) 0.11 2509	(14.71) 0.18 2509		
>3015	-647.04***	-288.01***	-359.03***	0.45	0.55
	(23.56) 0.27 2154	(19.15) 0.10 2154	(15.40) 0.21 2154		
>4299	-633.72***	-287.13***	-346.58***	0.45	0.55
	(24.77) 0.27 1798	(19.52) 0.11 1798	(15.70) 0.22 1798		
>5921	-652.28***	-294.91***	-357.37***	0.45	0.55
	(25.87) 0.31 1440	(19.96) 0.14 1440	(15.91) 0.27 1440		
>8825	-691.51***	-323.28***	-368.23***	0.47	0.53
	(24.79) 0.43 1081	(21.10) 0.18 1081	(15.46) 0.35 1081		
>14311	-468.58***	-216.86***	-251.72***	0.46	0.54
	(30.89) 0.25 727	(24.86) 0.10 727	(19.16) 0.20 727		
>20175	-74.82	-96.78**	21.97	1.29	-0.29
	(46.50) 0.01 364	(40.99) 0.02 364	(27.39) 0.00 364		

*** p<0.01, ** p<0.05, * p<0.1

Table 13: Average change of (modern) CO_2 emission, GDP and emission intensity growth rates $(\times 10^4)$ over time and the log of GDP per capita for different periods and GDP per capita levels. Standard errors, R^2 and sample size underneath estimates.

(a) CO_2 per capita (modern) versus time

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-20.84***	-14.00***	-6.84***	0.67	0.33
	(0.66) 0.22 3572	(0.61) 0.13 3572	(0.29) 0.14 3572		
>1968	-11.94***	-6.88***	-5.07***	0.58	0.42
	(0.67) 0.10 2820	(0.62) 0.04 2820	(0.37) 0.06 2820		
>1978	4.78***	2.22**	2.56***	0.46	0.54
	(1.00) 0.01 1880	(0.98) 0.00 1880	(0.64) 0.01 1880		
>1988	-1.90	-5.89***	4.00***	3.10	-2.10
	(1.83) 0.00 940	(1.99) 0.01 940	(1.05) 0.02 940		

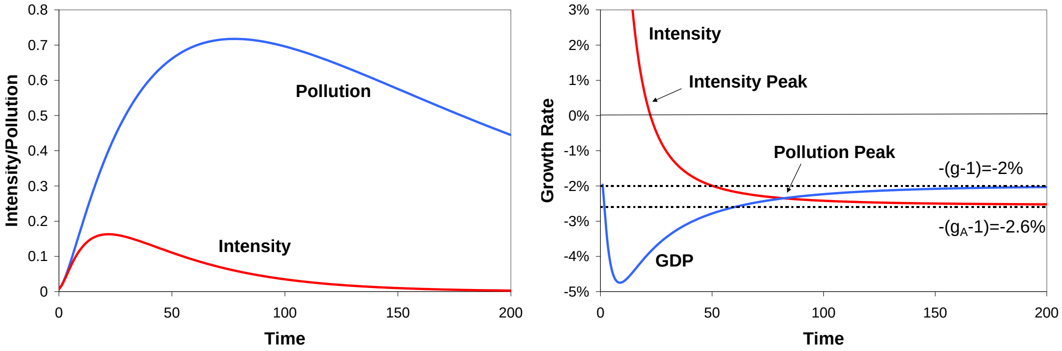
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

(b) CO_2 per capita (modern) versus log of GDP per capita

	$\bar{\beta}_P$	$\bar{\beta}_N$	$\bar{\beta}_Y$	$\bar{\beta}_N/\bar{\beta}_P$	$\bar{\beta}_Y/\bar{\beta}_P$
All	-585.31***	-426.03***	-159.28***	0.73	0.27
	(28.72) 0.11 3572	(25.44) 0.08 3572	(12.15) 0.05 3572		
>1078	-626.61***	-400.14***	-226.47***	0.64	0.36
	(25.07) 0.17 3221	(22.06) 0.10 3221	(12.16) 0.10 3221		
>1478	-617.64***	-373.10***	-244.54***	0.60	0.40
	(24.31) 0.19 2869	(21.26) 0.10 2869	(12.75) 0.12 2869		
>2029	-624.90***	-340.97***	-283.93***	0.55	0.45
	(23.71) 0.22 2509	(20.20) 0.11 2509	(13.19) 0.16 2509		
>3015	-593.66***	-288.01***	-305.64***	0.49	0.51
	(23.34) 0.24 2154	(19.15) 0.10 2154	(14.17) 0.18 2154		
>4299	-584.65***	-287.13***	-297.52***	0.49	0.51
	(24.46) 0.25 1798	(19.52) 0.11 1798	(14.95) 0.19 1798		
>5921	-606.91***	-294.91***	-312.00***	0.49	0.51
	(25.39) 0.29 1440	(19.96) 0.14 1440	(15.17) 0.23 1440		
>8825	-636.17***	-323.28***	-312.89***	0.51	0.49
	(24.21) 0.40 1081	(21.10) 0.18 1081	(14.27) 0.32 1081		
>14311	-424.16***	-216.86***	-207.30***	0.51	0.49
	(28.50) 0.24 727	(24.86) 0.10 727	(15.61) 0.20 727		
>20175	-129.95***	-96.78**	-33.17	0.74	0.26
	(44.91) 0.02 364	(40.99) 0.02 364	(24.57) 0.01 364		

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 14: Average change of (modern) CO_2 per capita emission, GDP per capita and emission intensity growth rates ($\times 10^4$) over time and the log of GDP per capita for different periods and GDP per capita levels. Standard errors, R^2 and sample size underneath estimates.



(a) Emissions and Intensity

(b) Emissions and Intensity Growth Rates

Figure 8: Emissions and Intensity: Levels and Growth Rates (Model, capital).

Households Furthermore, suppose that consumers are owners of the capital and the ones who purchase investment goods. Their budget constraint becomes $p_t^a a_t + p_t^c(c_t + i_t) = w_t + r_t k_t$, and the law of motion of capital is given by $k_{t+1} = (1-\delta)k_t + i_t$,where r_t is the rental rate of capital and δ is the rate of depreciation.

Market Clearing The additional market clearing constraints are those for capital, investment and non-agricultural consumption:

$$k_t = K_t,\ i_t = I_t \text{ and } c_t = C_t. \tag{20}$$

Numerical Example The definition of equilibrium is similar to before and is left unstated. As before, I also assume that the economy starts entirely within the agricultural sector (and hence with no endowment of capital). In addition to previous parameter assumptions, I also suppose that $\alpha = 0.33$, $\delta = 0.1$, $\beta = 0.96$ and $\nu = 0.0001$. The simulated emissions and emission intensities are shown in Figure 8(a) - both follow a hump shape. Figure 8(b), presents the growth rates of intensity and GDP over time. As before, intensity growth rates fall resulting in hump-shaped intensity. However, GDP growth is no longer constant and now follows a hump shape (much like it does in the data), due to a rising capital labor ratio driven by structural transformation.[21] Since the economy is now growing faster, emissions peak later than before. Thus, capital accumulation can be important in driving emissions, but it does not help explain why intensity growth rates change faster than GDP growth rates in the data. In fact, capital accumulation in the model results in greater changes in GDP growth, putting even more weight on the channel that the data indicates is less important.

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[21] For more details of this process see Gollin et al. (2002).

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