

ECONOMIC GROWTH, INDUSTRIALIZATION, AND THE ENVIRONMENT

JEVAN CHERNIWCHAN

ABSTRACT. This paper argues the compositional shift from agricultural to industrial production - industrialization - is a central determinant of changes in environmental quality as economies develop. A simple two-sector model of neoclassical growth and the environment in a small open economy is developed to examine how industrialization affects the environment. The model is estimated using sulfur emissions data for 68 countries over the period 1970-2000. The results show the process of industrialization is a significant determinant of observed changes in emissions: a 1% increase in industry's share of total output is associated with an 24% increase in the level of emissions per capita.

Keywords: Environment; Economic Growth; Industrialization; Pollution

JEL Classification: O41; O44; Q56

Date: November, 2010.

Department of Economics, The University of Calgary, 2500 University Dr. NW, Calgary, AB, T2N 1N4, Canada. Email: jcherniw@ucalgary.ca. Tel: (403) 220-3919. Fax: (403) 282-5262. I am grateful to Scott Taylor for helpful comments and guidance that significantly improved this paper. I would also like to thank Rob Oxoby and Irving Rosales for their comments and suggestions. Funding from the Social Science and Humanities Research Council of Canada is also acknowledged. The usual disclaimer applies.

1. INTRODUCTION

Over the past thirty years, emissions levels of key industrial pollutants have decreased in the developed world, but have increased in developing countries. This observation, known as the Environmental Kuznets Curve (or EKC), has dominated how researchers and policy makers think about the relationship between economic growth and the environment.¹ While there have been many attempts to explain the EKC, existing theories have not come to grips with three other puzzling features of the data: (i) there has been a great deal of cross-country convergence in pollution emissions over time, (ii) there is substantial variation in the emission intensities (emissions per unit of output) of industrial pollutants both over time and across countries and (iii) as a fraction of GDP, pollution abatement costs have been small and constant over time in the industrialized world.

This paper provides a theory of economic growth and the environment that explains these features of the data, and offers new testable implications. Specifically, the theory predicts cross-country convergence in pollution emissions as economies industrialize. The empirical results in turn demonstrate the process of industrialization is a significant determinant of observed changes in sulfur emissions: a 1% increase in industry's share of total output is associated with an 24% increase in the level of emissions per capita.²

I develop a simple two-sector neoclassical model of economic growth and the environment in a small open economy in which growth is driven by a combination of capital accumulation and technological progress. The model features two goods, each of which is produced using a combination of capital and labor: a clean agricultural good, and a dirty industrial good that produces pollution as a joint output. I assume the agricultural good is consumed while the capital intensive industrial good is used in investment. I adopt a simple Solow-type framework with a fixed savings rate and abatement intensity. Technological progress in the production of goods and abatement is exogenous.

¹For surveys of the literature on the EKC, see Barbier (1997) and Stern (2004).

²In the context of the literature, this finding is striking: existing empirical work has shown compositional changes are typically responsible for decreases in emissions levels. See for example, Selden et al. (1999) or Bruvoll and Medin (2003). It is however, consistent with Antweiler et al. (2001), who find strong compositional effects for sulfur.

In this context, the compositional shift from agricultural to industrial production as an economy grows - industrialization - drives changes in pollution levels during the transition to the balanced growth path. Development begins with rapid economic growth as capital is accumulated and this growth increases emissions in two ways. With growth, more output is produced and this increase in the scale of production causes emissions to rise. As capital becomes relatively more abundant, the composition of output shifts towards pollution intensive industrial production, leading to a further increase in pollution emissions. At the same time, improvements in the techniques of production arising from ongoing technological progress in abatement work to lower emissions.

If growth is initially rapid, then compositional shifts towards industrial production overwhelm technological progress in abatement, so emissions levels rise. As development proceeds, diminishing returns to capital cause growth and compositional changes to slow. Technological progress in abatement then occurs faster than emissions growth, so emissions levels fall.

Together, changes in the scale, composition and techniques of production during industrialization give rise to the EKC.³ While this interaction explains why an EKC could arise, it is important to note that the EKC is not a necessary result. Whether an EKC is observed depends on the initial capital stock and rate of technological progress in abatement; moreover, even when an EKC pattern is produced, these differ across countries. This finding is consistent with the evidence; the EKC is not a robust feature of the data.⁴

The process of industrialization does, however, generate convergence in cross-country emissions levels during the transition to the balanced growth path. Economy-wide diminishing returns to capital cause the scale and composition effects to decrease as capital accumulates. As a result, countries that differ only in their initial capital stock will exhibit convergence in pollution emission levels; the growth rate of pollution changes faster in poor countries than in rich countries. This occurs regardless of whether pollution levels are increasing or decreasing along the balanced growth path; and occurs regardless of the trade pattern.

³Copeland and Taylor (1994) term these the *scale*, *composition* and *technique* effects.

⁴See, for example, Stern and Common (2001) and Harbaugh et al. (2002).

Moreover, the model tells us that convergence is conditional on industrialization. There is, in fact, considerable evidence of convergence in pollution emissions over time, both within and across countries.⁵

As development proceeds, and more of the industrial good is produced domestically, expenditures on pollution abatement increase. However, because of diminishing returns to capital the growth rate of pollution abatement costs falls as industrialization occurs, meaning that growth rate of pollution abatement costs and income are roughly the same once an economy is industrialized. This fits with the data: the available evidence indicates that for members of the OECD, pollution abatement costs have been a small and constant fraction of GDP over time.⁶

To evaluate the theory, I log-linearize the model around the balanced growth path to derive an estimating equation linking emissions per capita in any period to emissions per capita in the previous period and additional controls.⁷ These controls include typical determinants of the balanced growth path, such as the savings rate and population growth, but also include a measure of industrialization. I formulate the estimating equation as a dynamic panel data model and estimate it using the Least Squares with Dummy Variables (LSDV) estimator suggested by Islam (1995). This approach allows me to directly estimate the effect of industrialization on pollution levels and evaluate the testable restrictions implied by the theory.

I estimate the model using a unique panel data set obtained by combining data on sulfur emissions (Stern, 2006), with data on population, savings and income from the Penn World Tables (Heston et al., 2009), and data on sectoral composition from the World Bank's World Development Indicators. There are two reasons for using data on sulfur emissions. First, while sulfur emissions have been studied extensively in the context of the EKC, there is little support for an EKC type relationship in the data (Stern and Common, 2001; Harbaugh et

⁵See, for example, Strazicich and List (2003), Lee and List (2004), Aldy (2006), Bulte et al. (2007) and Brock and Taylor (2010).

⁶See Table 2A of the 2006 OECD publication, "Pollution abatement and control expenditures in OECD countries", Paris: OECD Secretariat.

⁷This approach is commonly employed in the macroeconomics literature on income convergence. See, for example, Mankiw et al. (1992) and Islam (1995).

al., 2002). Hence, little is known about what forces are driving changes in sulfur dioxide pollution across countries. The second reason for doing so is data availability. Sulfur is one of two pollutants (carbon dioxide being the other) for which there is data on emissions for a large number of countries over a substantial period of time. The data set includes annual observations for 68 countries over the period 1970-2000.⁸

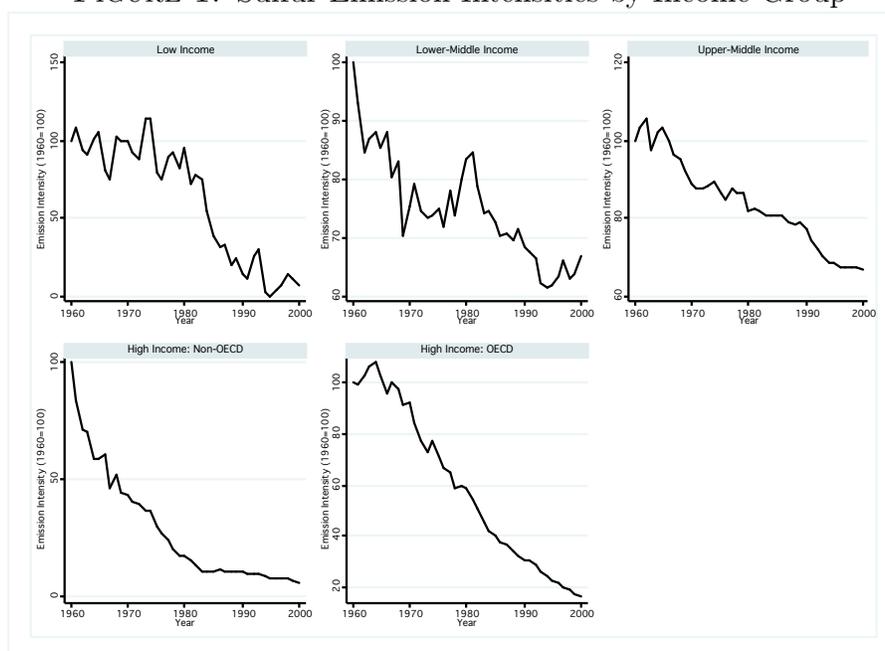
This paper contributes to the literature on economic growth and the environment in two ways. First, it makes a theoretical contribution by developing a model of the EKC that explains other features of cross-country pollution data not considered before. Specifically, I explain why, over time: (i) there has been cross-country convergence in pollution emissions, (ii) there has been variation in emission intensities across countries, and (iii) pollution abatement costs have been a small and constant fraction of the GDP in the industrialized world. Most existing theories focus solely on explaining the inverted-U shaped relationship between income and pollution (see for example, Selden and Song (1994), Lopez (1994), John and Pecchenino (1994), Stokey (1998), and Andreoni and Levinson (2001)), but do not match other features in the data.

The second contribution of this paper is empirical. This paper is the first to examine cross country convergence in sulfur emissions using a dynamic panel model. While many authors have previously examined the cross-country sulfur emissions data (see for example, Grossman and Krueger (1995), Stern and Common (2001), Harbaugh et al. (2002)), this study is the first to employ an empirical approach that is tied tightly to theory.

By introducing pollution into a simple neoclassical growth model, this paper bears close resemblance to the work of Brock and Taylor (2010). They develop an augmented version of the Solow model in which the EKC is generated through the interaction of scale and technique effects. In their one good model, emissions intensities decline at a constant rate over time. While a one good model may be a useful vehicle in which to study the behavior of pollutants that are produced by all or most economic activity (such as carbon dioxide), it may not be as useful for studying the behavior of other pollutants, which are mainly produced by

⁸The time period and the cross-country coverage was determined by data limitations imposed by the Penn World Tables and the World Development Indicators database.

FIGURE 1. Sulfur Emission Intensities by Income Group



industrial processes tied to specific sectors. In these cases, sectoral shifts brought about by development may be critical to consider. For example, consider Figure 1, which plots sulfur emission intensities by income group over the period 1960-2000. While emissions intensities are declining at a roughly constant rate for high income countries in the industrialized world, there is significant variation in emission intensities over time for low income countries that are currently in the process of industrializing. This suggests that changes in emission intensity induced by industrialization are an important part of development.

The rest of this paper proceeds as follows. Section 2 describes the model and establishes its equilibrium. Section 3 describes how the process of industrialization affects pollution. Section 4 outlines the empirical methodology and results. Section 5 concludes.

2. A MODEL OF ECONOMIC GROWTH AND THE ENVIRONMENT IN A SMALL OPEN ECONOMY

2.1. Supply. The economy consists of two sectors: agriculture and industry. The agricultural sector produces a consumption good, Y , while the industrial sector produces an investment good, X . Both sectors are perfectly competitive, with output prices 1 and p

respectively. Output from each sector can be traded internationally; p is fixed by world markets. Moreover, I assume trade is balanced and there are no barriers to trade. Each good is produced by combining capital and effective labor using a strictly concave and constant returns to scale production function. In addition, I assume both production functions satisfy the Inada conditions. Industrial production is capital intensive, while agriculture is labor intensive. The agricultural production function is given by:⁹

$$(1) \quad Y = H(K_Y, BL_Y)$$

where K_Y denotes capital used in agriculture, L_Y denotes labor used in agriculture and B represents the level of labor augmenting technology in the economy.¹⁰

Industrial production is dirty; that is, pollution, Z , is produced as a joint output. Following Copeland and Taylor (1994), I assume each unit of X produced generates Ω units of pollution as a joint output. Firms are, however, able to reduce the emissions of Z by allocating a fraction $\theta \in [0, 1]$ of output to abatement activities. Abatement is a constant returns to scale activity with the same factor requirements as X . With abatement, Ω can be interpreted as the level of abatement augmenting technology in the economy. The joint production technology is given by:

$$(2) \quad X = (1 - \theta) \times F(K_X, BL_X)$$

$$(3) \quad Z = a(\theta) \times \Omega \times F(K_X, BL_X)$$

where K_X denotes capital used in industry, L_X denotes labor employed in industry, and $a(\theta)$ is the abatement technology. I assume the abatement technology satisfies $a(0) = 1$, $a(1) = 0$ and $a'(\theta) < 0$, meaning the level of pollution decreases with abatement. In addition, I assume θ is constant; this is the environmental analogue of the fixed saving assumption in the Solow framework. With θ fixed, a constant fraction of industrial production is devoted

⁹Time indices are suppressed throughout.

¹⁰For simplicity, I assume labor augmenting technology is common to both sectors.

to mitigating pollution at any point in time. In what follows, I assume the abatement technology takes the form $a(\theta) = (1 - \theta)^{1/\eta}$, with $\eta \in (0, 1)$.

Factor markets are assumed to be perfectly competitive; firms face prices r and w for capital and effective labor services. In addition both capital and labor are supplied inelastically and are perfectly mobile across sectors, but neither is traded on international markets. At any point in time:

$$(4) \quad K = K_X + K_Y$$

$$(5) \quad L = L_X + L_Y$$

Pollution is costly; firms face an exogenous environmental tax $\tau > 0$ per unit of pollution.¹¹ Profits for an industrial firm are given by:

$$(6) \quad \pi_X = (1 - \tau e)X - rK_X - wBL_X$$

where $e = Z/X$ is the emission intensity of industrial production. Given the abatement technology, the total cost of polluting is equal to $\tau Z = \eta X$. Equation (6) can be rewritten as:

$$(7) \quad \pi_X = (1 - \eta)X - rK_X - wBL_X$$

where $(1 - \eta)$ is the effective producer price received by an industrial firm. Profits for an agricultural firm are given by:

$$(8) \quad \pi_Y = pY - rK_Y - wBL_Y$$

At any given point in time equilibrium in production is determined by the full employment of factors and free entry. Free entry ensures firms earn zero profits; the corresponding

¹¹It is important to note the assumption of fixed θ implies τ is increasing over time. This is consistent with reality: regulation of industrial pollutants has increased across the world since the early 1970s.

equilibrium conditions can be written as:

$$(9) \quad c^Y(w, r) = p$$

$$(10) \quad c^X(w, r, \tau) = (1 - \eta)$$

where $c^Y(w, r)$ is the unit cost function for the production of agriculture and $c^X(w, r, \tau)$ is the unit cost function corresponding to the production of a unit of output of the industrial good net of abatement. These conditions indicate in equilibrium, unit costs are equal to the effective prices faced by firms in both sectors.

Given X is, by assumption, more capital intensive than Y for all factor prices, (9) and (10) will intersect at most once. This intersection determines factor prices. Moreover, by Shepard's Lemma, evaluation of the gradients of $c^X(w, r)$ and $c^Y(w, r)$ at this intersection point will yield the unit factor demands for X and Y . The full employment conditions can be written as:

$$(11) \quad K = c_r^X X + c_r^Y Y$$

$$(12) \quad BL = c_w^X X + c_w^Y Y$$

where $c_r^X = \partial c^X(w, r, \tau) / \partial r = a_{KX}(w, r, \tau)$, $c_w^X = \partial c^X(w, r, \tau) / \partial w = a_{BLX}(w, r)$, $c_r^Y = \partial c^Y(w, r) / \partial r = a_{KY}(w, r)$, and $c_w^Y = \partial c^Y(w, r) / \partial w = a_{BLY}(w, r)$ are the unit factor demands in the production of X and Y .

Given the environmental tax, and the assumptions on markets and production, at any point in time, production in this economy can be represented with a revenue function:

$$(13) \quad R(p, \tau, K, BL) \equiv \max_{X, Y, Z} \{X + pY - \tau Z : (X, Y) \in T(K, BL, Z)\}$$

where $T(K, BL, Z)$ denotes the production possibility set. $R(p, \tau, K, BL)$ is homogenous of degree one in both prices and endowments. As before, the total cost of polluting is equal to $\tau Z = \eta X$.

The revenue from the environmental tax is rebated to consumers in a lump-sum fashion. This means the economy can be represented with a gross national product (GNP) function:

$$(14) \quad G(p, K, BL) = R(p, \tau, K, BL) + \tau Z$$

Let $\Phi(p, K, BL)$ denote the value share of industrial production in national income.¹² Aggregate emissions can be rewritten as:

$$(15) \quad Z = a\Omega\Phi(p, K, BL)G(p, K, BL)$$

where $a = a(\theta)/(1 - \theta)$ is a constant. Emissions are a function of the techniques of abatement, $a\Omega$, the composition of national output, $\Phi(p, K, BL)$ and the scale of the economy, $G(p, K, BL)$.

2.2. Demand. Throughout, I assume a constant fraction, s , of income is saved by consumers and the rest is spent on consumption of the agricultural good. At any point in time aggregate consumption is given by:

$$(16) \quad C = (1 - s)G(p, K, BL)/p.$$

Similarly, aggregate investment is given by:

$$(17) \quad I = sG(p, K, BL).$$

where $s \in (0, 1)$.

2.3. International Markets. I consider a small open economy; both goods are traded on world markets. Moreover, I assume trade is balanced, so at any point in time, any excess demand or supply for X and Y will be satisfied by world markets. This means:

$$(18) \quad Y + Y^* = (1 - s)G(p, K, BL)/p$$

$$(19) \quad X + X^* = sG(p, K, BL)$$

¹²Note $\Phi(p, K, BL) = X/G(p, K, BL)$, so $\Phi(p, K, BL) \in (0, 1)$.

where Y^* and X^* denote purchases of the agricultural good and industrial good from international markets.

2.4. **Growth.** Following Brock and Taylor (2010), I assume constant proportional rates of population growth, n , labor-augmenting technological progress, g_B , and technological progress in abatement, g_A , so:

$$(20) \quad \dot{L} = nL$$

$$(21) \quad \dot{B} = g_B B$$

$$(22) \quad \dot{\Omega} = -g_A \Omega$$

where dots over variables denote time derivatives.

Capital accumulates through investment I :

$$(23) \quad \dot{K} = I - \delta K$$

where δ is the rate of capital depreciation. Given equation (17), equation (23) can be rewritten as:

$$(24) \quad \dot{K} = sG(p, K, BL) - \delta K$$

Given initial values for K , L , B , and Ω , equations (20)-(22) and (24) define the dynamics of the economy.

Recall the production and GNP functions are homogeneous of degree one in K and BL . Hence, the model can be reformulated in intensive form:

$$(25) \quad G(p, k) = x + py$$

$$(26) \quad x = l_x(1 - \theta)f(k_x)$$

$$(27) \quad y = (1 - l_x)h(k_y)$$

$$(28) \quad k = l_x k_x + (1 - l_x)k_y$$

$$(29) \quad \dot{k} = sG(p, k) - [\delta + n + g_B]k$$

$$(30) \quad z = a\Omega\phi(p, k)G(p, k)$$

where $l_x = L_x/L \in [0, 1]$ is the share of labor in industrial production, $k = K/BL$ is capital per effective worker, $k_x = K_X/BL_X$ and $k_y = K_Y/BL_Y$ are the capital to effective labor ratios employed in industrial and agricultural production when production is diversified, $x = X/BL$, $y = Y/BL$, and $z = Z/BL$ are industrial production per effective worker, agricultural production per effective worker and pollution per effective worker, $f(k_x) = F(K_x/BL_x, 1)$, and $h(k_y) = H(K_y/BL_y, 1)$ are the intensive form production functions, $G(p, k) \equiv G(p, K/BL, 1)$ is income per effective worker and $\phi(p, k) \equiv l_x(1 - \theta)f(k_x)/G(p, k)$ is the value share of industrial production in income.¹³

2.5. The Balanced Growth Path. Given equations (25)-(28), GNP can be rewritten as:

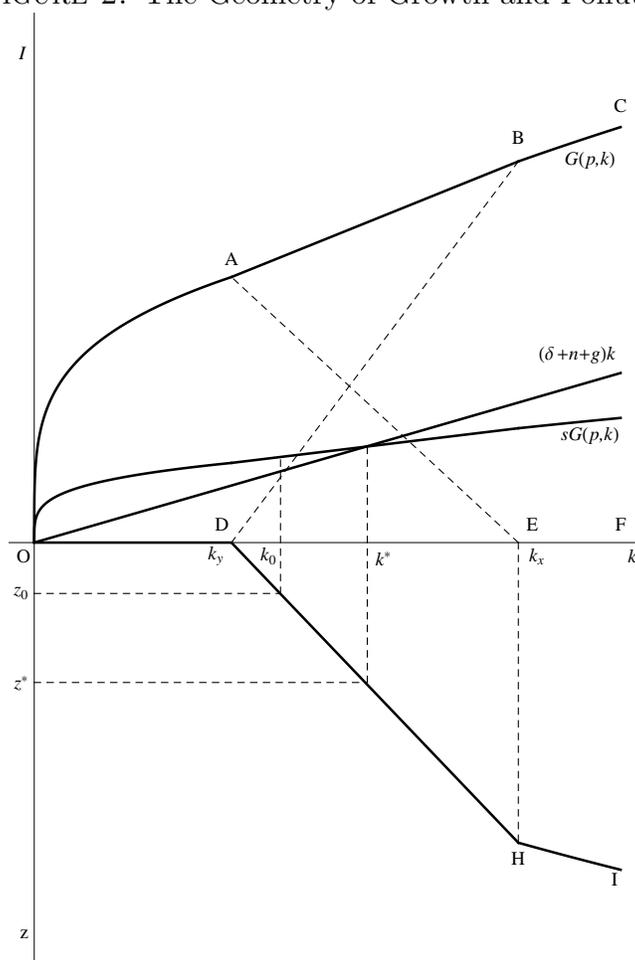
$$(31) \quad G(p, k) = \begin{cases} ph(k) & \text{if } k \leq k_y \\ \gamma_x(1 - \theta)f(k_x) + (1 - \gamma_x)ph(k_y) & \text{if } k \in (k_y, k_x) \\ (1 - \theta)f(k) & \text{if } k \geq k_x \end{cases}$$

where $\gamma_x = ((k - k_y)/(k_x - k_y))$ and $k_x > k_y$. For a given p , $G(p, k)$ summarizes the pattern of production in the economy. If $k \leq k_y$, the economy specializes in agricultural production. Similarly, if $k \geq k_x$ the economy specializes in industrial production. Finally, if $k \in (k_y, k_x)$, production is diversified and the economy produces both goods.

Clearly, the domestic production pattern depends on the level of capital per effective worker in the economy. This is governed by investment. From (29), for any level of k , a fraction s of national income, $G(p, k)$, is invested in new capital, while a portion of the existing capital stock per effective worker depreciates at rate $(\delta + n + g_B)$. The difference between investment and depreciation determines the growth of k . Let k^* denote the equilibrium level of k ; that is, let k^* denote the level of k for which the growth rate of k equals zero. If $k < k^*$,

¹³To see the relationship between ϕ and Φ , note: $\Phi(p, K, BL) = X/G(p, K, BL) = (1 - \theta)F(K_x, BL_x)/G(p, K, BL)$. Given $G(p, K, BL)$ is homogenous of degree one in endowments and $F(K_x, BL_x)$ is constant returns to scale, we have $(1 - \theta)F(K_x, BL_x)/G(p, K, BL) = (BL_x/BL)((1 - \theta)F(K_x/BL_x, 1)/G(p, K/BL, 1))$. Define $\phi(p, k) = l_x(1 - \theta)f(k_x)/G(p, k)$. Hence $\phi(p, k) \equiv \Phi(p, K, BL)$.

FIGURE 2. The Geometry of Growth and Pollution



investment exceeds the rate of depreciation and the capital stock per effective worker must grow over time; conversely, if $k > k^*$, depreciation exceeds investment and the capital stock per effective worker must be declining. If $k = k^*$, investment equals depreciation, and the economy is on a balanced growth path.

The relationship between production and capital accumulation is illustrated in Figure 2, using the diagrammatic techniques suggested by Deardorff (1974) for a given level of the abatement technology. This diagram summarizes the behavior of the economy in terms of capital per effective worker for given prices. Income in the economy is given by the line $OABC$. Savings and effective depreciation are given by the curves $sG(p, k)$ and $(\delta + n + g_B)k$ respectively. The domestic production of x is given by the line $ODBC$ and the domestic

production of y valued in terms of x is given by the line $OAEF$. The level of pollution produced for a given level of the abatement technology is given by the line $ODHI$.

Together, production and investment determine the pattern of trade. Domestic demand for the investment good is given by $sG(p, k)$, while domestic supply is given by:

$$(32) \quad x = \begin{cases} 0 & \text{if } k \leq k_y \\ \gamma_x(1 - \theta)f(k_x) & \text{if } k \in (k_y, k_x) \\ G(p, k) & \text{if } k \geq k_x \end{cases}$$

If $k \leq k_y$, the economy exports the agricultural good and imports the industrial good. The country remains a net exporter of agricultural products until domestic demand equals domestic supply, which is given where the lines AE and BD intersect on Figure 2. Denote the corresponding level of capital per effective worker by \bar{k} . Then, for any $k > \bar{k}$, the country is a net exporter of the industrial good. Formally,

$$(33) \quad E(p, k) = \begin{cases} -sG(p, k) & \text{if } k \leq k_y \\ (1 - s)\gamma_x(1 - \theta)f(\bar{k}_x) - s(1 - \gamma_x)ph(\bar{k}_y) & \text{if } k \in (k_y, k_x) \\ (1 - s)G(p, k) & \text{if } k \geq k_x \end{cases}$$

where $E(p, k)$ denotes net exports of the industrial good.¹⁴

From Figure 2, it is clear the dynamics of k are determined completely by investment and depreciation. Moreover, given diminishing returns to capital, the economy converges to a balanced growth path, which is given by the intersection of the investment curve and the effective depreciation curve. The balanced growth path is the long run equilibrium of the economy.

Proposition 1. *Given any $k(0) > 0$, and fixed p , the economy converges to a unique stable balanced growth path.*

Proof: See the appendix.

¹⁴Given trade is balanced, trade in the agricultural good can be recovered directly from (33).

Proposition 1 indicates the economy converges to a unique level of capital per effective worker in the long run for given world prices, regardless of initial conditions. However, the composition of production along the balanced growth path is dependent on the specific features of the economy. Given the correspondence between X and Z , this means the long-run behavior of emissions also depends on the economy's attributes. If the effective rate of depreciation is large enough, or savings rate is sufficiently low, $k^* \leq k_y$, the economy will specialize in agricultural production and will be an importer of industrial goods along the balanced growth path. Conversely, if savings are sufficiently high, or depreciation is sufficiently low, $k^* \geq k_x$, the economy will specialize in industrial production and will import agricultural goods along the balanced growth path. If $k^* \in (k_y, k_y)$, the economy will produce both goods in the long run, but the relative shares of agriculture and industry in total output depend on parameters. In what follows, I restrict attention to the case where the economy is diversified and assume $k^* \in (k_y, k_y)$.

As the economy approaches the balanced growth path, national income and the capital stock both grow at a constant rate $g_B + n$. From (30) and (31) it is easy to show that when the economy is diversified on the balanced growth path, the growth rate of aggregate emissions, g_Z , is given by $g_Z = n + g_B - g_A$. In the long run, pollution emissions will increase if output growth outstrips the rate of improvement in abatement technology, that is, if $g_A < n + g_B$. Similarly, pollution emissions will decrease in the long run if $g_A > n + g_B$, and technological progress in abatement occurs faster than output growth. It is important to note the compositional changes associated with industrialization play no role in the long run as the composition of production is fixed.

3. INDUSTRIALIZATION AND POLLUTION

While industrialization does not affect emissions growth in the long run, it does play a role in determining emissions during the transition to the balanced growth path. When the economy is not on the balanced growth path, the growth rate of pollution emissions can be

written as:

$$(34) \quad \frac{\dot{Z}}{Z} = -g_A + \frac{\dot{\phi}(p, k)}{\phi(p, k)} + \left(\frac{\dot{G}(p, k)}{G(p, k)} + n + g_B \right)$$

where \dot{Z}/Z is the growth rate of aggregate pollution, g_A is the growth rate of technological progress in abatement, $\dot{\phi}(p, k)/\phi(p, k)$ is the growth rate of the value share of industry in national income and $\dot{G}(p, k)/G(p, k)$ is the growth rate of national income per effective worker.¹⁵ The growth rate of pollution depends on the long run trend (g_Z), but varies with changes in both the size of the economy and the composition of national output during the transition to the balanced growth path. Scale and composition are both functions of the stock of capital per effective worker in the economy; this means the transitional behavior of aggregate emissions will be determined by the growth rate of capital per effective worker.¹⁶ Moreover, the transitional changes in scale and composition depend explicitly on the magnitude of the economy's initial capital stock relative to its level on the balanced growth path.

I assume the economy is initially endowed with a level of capital per effective worker that is smaller than its level along the balanced growth path; that is, I assume $k_0 < k^*$. In this case, growth is generated through a combination of capital accumulation and technological progress as the economy transitions towards the balanced growth path.

3.1. Industrialization and the EKC. When the economy is on the balanced growth path, the growth rate of aggregate pollution is determined by the underlying fundamentals of the economy (the rate of population growth, and the rates of technological progress in both labor and abatement-augmenting technologies respectively). During the transition to the balanced

¹⁵Using the terminology of Copeland and Taylor (1994), the terms on the left hand side of (34) are the *technique effect* (g_A), the *composition effect* ($\dot{\phi}(p, k)/\phi(p, k)$) and the *scale effect* ($\dot{G}(p, k)/G(p, k) + n + g_B$). The technique effect captures the change in pollution that arises from a change in abatement technology. The composition effect reflects the effect of a change in the mix of production on pollution levels. The effect of a change in the size of the economy on emissions is captured by the scale effect. It is useful to note the scale effect is comprised of two elements; the long-run component, $(n + g_B)$, which is driven by technical change in production and population growth and the short-run component ($\dot{G}(p, k)/G(p, k)$), which is driven by capital accumulation during the transition to the balanced growth path.

¹⁶Note (34) can be rewritten as $\dot{Z}/Z = g_Z + (\varepsilon_{\phi k} + \varepsilon_{Gk})(\dot{k}/k)$, where $\varepsilon_{\phi k} = (\partial\phi(p, k)/\partial k)(k/\phi(p, k))$ and $\varepsilon_{Gk} = (\partial G(p, k)/\partial k)(k/G(p, k))$ are the elasticities of composition and output, respectively.

growth path deviations from this rate occur as a consequence of capital accumulation. As a result, the time path of aggregate emissions is not necessarily monotonic:

Proposition 2. *Assume growth is sustainable, so $g_Z < 0$. Then, there exists some $k^p < k^*$ such that for $k_0 < k^p$, aggregate emissions peak necessarily during the transition to the balanced growth path. If $k_0 \geq k^p$, aggregate emissions decline monotonically as the economy approaches the balanced growth path.*

Proof: See the appendix.

Proposition 2 indicates the EKC can arise when countries industrialize. To see the intuition for this result, consider an economy that is initially endowed with a very low level of capital (that is, suppose $k_0 < k^p$). With a low level of capital, the economy is relatively labor abundant; with fixed world prices, this means the economy initially has a comparative advantage in the production of agricultural goods. As a result, most factors are employed in agricultural production and little industrial production occurs. Because the economy is open to trade, some of the agricultural production is consumed while the rest is exported. These exports are used to finance purchases of industrial goods from international markets, which increases the capital stock and makes capital relatively more abundant. This stimulates industrialization; with the increase in capital factors are drawn out of agriculture and into industry, increasing the domestic production of industrial goods. As capital accumulates, more factors are drawn out of agriculture and into industry, furthering industrialization.

The process of industrialization increases emissions in two ways: (i) through increases in the scale of production as more output is produced, and (ii) through shifts in the composition of output towards pollution intensive industrial production as capital becomes relatively more abundant. At the same time improvements in the techniques of production from ongoing technological progress in abatement work to lower emissions.

Initially, changes in the scale and composition of production from industrialization overwhelm technological progress in abatement, causing emissions levels to rise. As development proceeds, diminishing returns to capital causes these changes to slow, meaning technological

progress in abatement occurs faster than emissions growth, so emissions levels fall. This process yields the EKC.

While it has long been recognized economic growth can affect the environment through changes in the scale, composition and techniques of production, compositional changes have, for the most part, been ignored in the existing theoretical literature.¹⁷ Instead, most theories adopt a one good framework which eliminates the possibility of compositional effects.¹⁸ While one-good models may be useful for the study of pollutants that are produced by most economic activity (such as carbon dioxide), they may not be as useful for studying the behaviors of other pollutants, which are mainly produced by industrial processes tied to specific sectors. In these cases, sectoral shifts brought about by development are critical to consider; a one good framework will obscure the mechanisms driving changes in emissions.

It is also important to note the EKC is not a necessary result; the existence of the EKC depends both on the particulars of technology and the initial endowment of capital per effective worker. Moreover, even when an EKC is produced, it is not unique path.¹⁹ This is consistent with the empirical evidence; as Stern and Common (2001) and Harbaugh et al. (2002) demonstrate, the EKC is not a robust feature of the data.

While Proposition 2 establishes the possibility of an EKC, it reveals little about the role of international trade in determining the pattern of aggregate emissions over time. International trade is often viewed as an alternative abatement mechanism for economies by allowing dirty domestic production to be replaced with imports from international markets.²⁰ Under this view, observed downturns in aggregate emissions are generated as a byproduct of trade as

¹⁷The exception to this is the “Sources of Growth” analysis presented in Copeland and Taylor (2003), Ch. 3.

¹⁸See, for example, Lopez (1994), John and Pecchenino (1994), Stokey (1998), Andreoni and Levinson (2001), Brock and Taylor (2010) and Criado et al. (Forthcoming).

¹⁹To see this, consider two countries that differ only in their initial level of the abatement technology. If the two countries differ only in their initial abatement technology, emissions in each country must peak at the same level of capital per effective worker, k^p . However, the peak level of emissions in each country will not be the same; the country with the better initial abatement technology will have lower emissions. If, instead, the two countries share the same initial level of abatement technology, but differ in size, the economy that is larger will have greater emissions everywhere, even though the two countries could have the same level of capital per effective worker at all points in time.

²⁰See Copeland and Taylor (2004).

domestic production patterns shift. For this to be true, the EKC must depend explicitly on the trade pattern.

Proposition 3. *Assume an EKC is generated during the transition to the balanced growth path. The EKC is independent of the trade pattern.*

Proof: See the appendix.

To see the intuition for this result, note when the economy is diversified capital accumulation increases the domestic supply of industrial goods more than domestic demand. This means the trade pattern can only change via industrialization in cases when the economy is endowed with a low level of capital per effective worker and initially imports industrial goods; if the economy is initially a net exporter of industrial production, capital accumulation simply increases the net exports of the industrial good. However, in either case, capital accumulation spurred by industrialization and ongoing technological progress in abatement can interact to generate an EKC, which means the EKC is not driven by the pattern of trade.

This is not to say international trade plays no role in determining emissions levels; in the model, trade plays an important role by facilitating the industrialization process. It does, however, suggest changes in international trade patterns are not a necessary condition for improvements in environmental quality as a country industrializes; trade need not function as an abatement mechanism for an EKC to arise.

3.2. **Convergence.** While it does not yield an EKC necessarily, the process of industrialization does generate convergence:

Proposition 4. *Suppose Country A and Country B differ only in their initial endowment of capital per effective worker, and suppose Country A is initially endowed with a higher level of capital per effective worker; that is, suppose $k_0^A > k_0^B$. Then, pollution emissions levels in Country A and Country B will converge as economies industrialize.*

Proof: See the appendix.

This finding offers a simple explanation for observed changes in pollution emissions over time.²¹ As capital accumulates, changes in the composition and scale of the economy cause the domestic supply of the industrial good to increase, increasing pollution. Diminishing returns to capital cause these increases to slow, meaning pollution levels approach their long run trend as the economy industrializes.²² As a result, countries that only differ in their initial endowment of capital per effective worker will exhibit convergence in pollution emissions levels; the growth rate of pollution emissions will change faster in poor countries than in rich countries.

The compositional changes created by industrialization play a key role in determining the path of emissions during convergence because the level of pollution is tied directly to the level of output in the industrial sector. In this case, the scale effect does not fully capture the effects of growth on pollution; industrial output grows faster than national income during the transition to the balanced growth path. This means convergence must depend explicitly on the level of industrialization.

Two other aspects of the convergence process warrant discussion. First, changes in trade patterns are not necessary for convergence to occur. As indicated previously, international trade is often viewed as an alternative abatement mechanism for economies by allowing dirty domestic production to be replaced with imports from international markets; hence, it may be natural to think trade causes convergence as economies shed dirty production. If this is true, convergence must depend explicitly on the trade pattern. As the following proposition indicates, this is not the case; changes in trade patterns are not necessary for convergence to occur.

Proposition 5. *Convergence is independent of the trade pattern.*

Proof: See the appendix.

²¹A number of authors have documented convergence in pollution: see, for example, Strazicich and List (2003), Lee and List (2004), Aldy (2006), Bulte et al. (2007) and Brock and Taylor (2010).

²²Convergence occurs regardless of whether pollution levels are increasing or decreasing on the balanced growth path.

The intuition for this result is similar to that of Proposition 3 as convergence and the EKC are both generated through capital accumulation during the transition to the balanced growth path. If an economy is a net exporter of industrial goods both initially and on the balanced growth path, then there will be no change in the trade pattern during the transition to the balanced growth path because capital accumulation simply increases the net exports of the industrial good as industrialization occurs. If instead an economy is a net importer of industrial goods initially but a net exporter on the balanced growth path, the trade pattern will change during the transition to the balanced growth path. Convergence will occur in either case; this means convergence is not driven by the pattern of trade.

Convergence also implies that pollution abatement costs will account for a constant fraction of output as an economy approaches the balanced growth path. As an economy grows and domestic industrial production increases, pollution abatement expenditures increase. However, because of diminishing returns to capital, the growth rate of pollution abatement costs falls as industrialization occurs. This means the growth rate of pollution abatement costs and national income are roughly the same once an economy is industrialized. This corresponds with the available data: in the OECD, pollution abatement costs have been a small and constant fraction of GDP over time.

4. EMPIRICAL EVIDENCE

The model contains two empirical predictions about convergence in emissions. If all countries share parameter values (and share balanced growth paths), then all countries converge to the same level of pollution emissions per capita and the model predicts *Absolute Convergence in Emissions per capita* (ACE). If, instead, countries are heterogeneous, the model predicts *Conditional Convergence in Emissions per capita* (CCE), meaning that any two countries will converge to the same level of pollution emissions per capita only if they share the same parameter values. In either case, convergence will also depend on the extent of industrialization.

4.1. **Estimating Equation.** To evaluate the theory's predictions about convergence, I derive an estimating equation from the model. To begin, rewrite equation (34) in terms of pollution per effective worker:

$$(35) \quad \frac{\dot{z}(t)}{z(t)} = -g_A + \frac{\dot{\phi}(p, k(t))}{\phi(p, k(t))} + \frac{\dot{G}(p, k(t))}{G(p, k(t))}$$

where, as before, $-g_A$ is the technique effect, $\dot{\phi}(p, k(t))/\phi(p, k(t))$ is the composition effect, and $\dot{G}(p, k(t))/G(p, k(t))$ is the scale effect.

Using the fact $\dot{\phi}(p, k(t))/\phi(p, k(t)) = \varepsilon_{\phi k}(\dot{k}(t)/k(t))$ and $\dot{G}(p, k(t))/G(p, k(t)) = \varepsilon_{Gk}(\dot{k}(t)/k(t))$ (where $\varepsilon_{\phi k}$ and ε_{Gk} denote the elasticities of composition and output), rewrite equation (35) as:

$$(36) \quad \frac{\dot{z}(t)}{z(t)} = -g_A + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) \frac{\dot{G}(p, k(t))}{G(p, k(t))}$$

Next, approximate growth in emissions per effective worker and capital per effective worker over a period $(t_1 - t_0)$. This yields:

$$(37) \quad \frac{\ln(z(t_1)/z(t_0))}{(t_1 - t_0)} = -g_A + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) \frac{\ln(G(t_1)/G(t_0))}{(t_1 - t_0)}$$

To obtain a discrete approximation of the growth rate of income per capita, log-linearize the model around the balanced growth path:

$$(38) \quad \ln(G(t_1)/G(t_0)) = (1 - e^{-\lambda(t_1-t_0)})(\ln G^* - \ln G(t_0))$$

where G^* is the level of income per effective worker on the balanced growth path and $\lambda = (1 - \varepsilon_{Gk})(\delta + n + g)$ is the speed of convergence. Substitute equation (38) into equation (37), yielding:

$$(39) \quad \frac{\ln(z(t_1)/z(t_0))}{(t_1 - t_0)} = -g_A + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) \frac{(1 - e^{-\lambda(t_1-t_0)})}{(t_1 - t_0)} (\ln G^* - \ln G(t_0))$$

Note $G(t_0) = z(t_0)/a\Omega(t_0)\phi(t_0)$, and at any point in time $z(t) = z^c(t)/B(t)$, where $z^c(t)$ denotes emissions per capita at time t . Given $B(t) = e^{g_B t}B(0)$ and $\Omega(t) = e^{-g_A t}\Omega(0)$, where

$B(0)$ and $\Omega(0)$ are the initial levels of the production and abatement technologies, rewrite equation (39) in per capita terms as:

$$\begin{aligned}
(40) \quad \frac{\ln z^c(t_1) - \ln z^c(t_0)}{(t_1 - t_0)} = & - \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) \frac{(1 - e^{-\lambda(t_1-t_0)})}{(t_1 - t_0)} \ln z^c(t_0) \\
& + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) \frac{(1 - e^{-\lambda(t_1-t_0)})}{(t_1 - t_0)} \ln \phi(t_0) \\
& + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) \frac{(1 - e^{-\lambda(t_1-t_0)})}{(t_1 - t_0)} \ln G^* \\
& + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) \frac{(1 - e^{-\lambda(t_1-t_0)})}{(t_1 - t_0)} (\ln a + \ln \Omega(0) + \ln B(0)) \\
& + \left(-g_A + g_B \left(1 + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t_1-t_0)}) t_0 \right) \right)
\end{aligned}$$

From (40), it is readily apparent that the growth rate of pollution emissions per capita over the period $(t_1 - t_0)$ is decreasing in the initial level of pollution emissions per capita ($\ln z^c(t_0)$). *Ceteris paribus*, this indicates pollution levels are converging. However, this convergence occurs conditionally on industrialization; the growth rate of pollution emissions per capita is increasing in the initial value share of industrial output in national income.

Equation (40) also indicates how differences in both initial conditions and endpoint affect emissions growth during convergence. Clearly, an increase in an economy's endowment of the production technology (an increase in $B(0)$), or a decrease in the initial effectiveness in the abatement technology (an increase in $\Omega(0)$) increases the growth rate of emissions. Similarly, a decrease in the economy's level of income per effective worker on the balanced growth path (a decrease in G^*) will lower the growth rate of emissions.

I reformulate (40) as a dynamic panel data model, yielding:

$$\begin{aligned}
(41) \quad \ln z^c(t_1) = & \left(1 - \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t_1-t_0)}) \right) \ln z^c(t_0) \\
& + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t_1-t_0)}) \ln \phi(t_0) \\
& + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t_1-t_0)}) \ln G^*
\end{aligned}$$

$$\begin{aligned}
& + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t_1 - t_0)}) (\ln a + \ln \Omega(0) + \ln B(0)) \\
& + (t_1 - t_0) \left(-g_A + g \left(1 + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t_1 - t_0)}) t_0 \right) \right)
\end{aligned}$$

If it is assumed all countries share the same balanced growth path and there is ACE, $((\varepsilon_{\phi k} + \varepsilon_{Gk})/\varepsilon_{Gk}) (1 - e^{-\lambda(t_1 - t_0)}) (\ln G^* + \ln a + \ln \Omega(0) + \ln B(0))$ is a time-invariant individual country effect. In the conventional notation of the panel data literature, this equation can be rewritten as:

$$(42) \quad \ln z_{i,t}^c = \beta_1 \ln z_{i,t-\tau}^c + \beta_2 \ln \phi_{i,t-\tau} + \eta_i + \mu_t + \epsilon_{i,t}$$

where

$$\begin{aligned}
\beta_1 & = \left(1 - \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t-\tau)}) \right) < 1 \\
\beta_2 & = \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t-\tau)}) > 0 \\
\eta_i & = ((\varepsilon_{\phi k} + \varepsilon_{Gk})/\varepsilon_{Gk}) (1 - e^{-\lambda(t-\tau)}) (\ln G^* + \ln a + \ln \Omega(0) + \ln B(0)) \\
\mu_t & = (t - \tau) \left(-g_A + g \left(1 + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t-\tau)}) \tau \right) \right)
\end{aligned}$$

and ϵ_{it} is a transitory error term with mean zero.

If instead countries are assumed to be heterogenous and there is CCE, the time-invariant individual country effect is given by $((\varepsilon_{\phi k} + \varepsilon_{Gk})/\varepsilon_{Gk}) (1 - e^{-\lambda(t_1 - t_0)}) (\ln a + \ln \Omega(0) + \ln B(0))$.

In this case, equation (41) can be rewritten as:

$$(43) \quad \ln z_{i,t}^c = \beta_1 \ln z_{i,t-\tau}^c + \beta_2 \ln \phi_{i,t-\tau} + \beta_3 \ln G_{i,t-\tau}^* + \eta_i + \mu_t + \epsilon_{i,t}$$

where

$$\begin{aligned}
\beta_1 & = \left(1 - \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t-\tau)}) \right) < 1 \\
\beta_2 = \beta_3 & = \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t-\tau)}) > 0
\end{aligned}$$

$$\eta_i = ((\varepsilon_{\phi k} + \varepsilon_{Gk})/\varepsilon_{Gk}) (1 - e^{-\lambda(t-\tau)})(\ln a + \ln \Omega(0) + \ln B(0))$$

$$\mu_t = (t - \tau) \left(-g_A + g \left(1 + \left(\frac{\varepsilon_{\phi k} + \varepsilon_{Gk}}{\varepsilon_{Gk}} \right) (1 - e^{-\lambda(t-\tau)})\tau \right) \right)$$

and ε_{it} is again a transitory error term with mean zero.

With data on G^* , equation (43) could be estimated directly. Unfortunately, such data is not available. To circumvent this problem, I proxy for G^* using observable determinants of the balanced growth path: the savings rate, s , and the rate of population growth, n .²³ The model can then be rewritten as:

$$(44) \quad \ln z_{i,t}^c = \beta_1 \ln z_{i,t-\tau}^c + \beta_2 \ln \phi_{i,t-\tau} + \beta_3 \ln s_{i,t} + \beta_4 \ln(\delta + n + g_B)_{i,t} + \eta_i + \mu_t + \varepsilon_{i,t}$$

where β_1 , β_2 , β_3 , η_i , μ_t , and $\varepsilon_{i,t}$ are defined as before, and $\beta_2 = \beta_3 = -\beta_4$.

By rewriting (40) in the form of (42) or (44), it is natural to think of the time-invariant individual country effect as a fixed effect. While many approaches are available to estimate panel models with fixed effects, here I follow the approach of Islam (1995) and use a Least Squares with Dummy Variables (LSDV) estimator.²⁴

4.2. Data. To estimate equations (42) and (44) I employ data on sulfur emissions. There are two reasons for doing so. First, while sulfur has been studied extensively in the context of the EKC, there is little support for an EKC type relationship in the data (Stern and Common, 2001; Harbaugh et al., 2002). Hence, little is known about what forces are driving changes in sulfur pollution across countries. The second reason for doing so is data availability. Sulfur is one of two pollutants (carbon dioxide being the other) for which there is data on emissions for a large number of countries over a substantial period of time.

²³Strictly speaking, G^* also depends on the depreciation rate, δ , the rate of technology, g_B and the world price p , which are also unobserved. To deal with the unobservability of δ and g_B , I follow Mankiw et al. (1992) and assume $\delta + g_B = 0.05$. Because p is assumed to be constant across time and countries, it will be subsumed by the country-specific effect.

²⁴Caselli et al. (1996) are critical of this approach because of possible endogeneity arising from having a lagged dependent variable on the right hand side and advocate using the generalized methods of moments estimator of Arellano and Bond (1991). However, their approach has been shown to be severely biased in the growth context. For further discussion see Durlauf et al. (2005).

The data set was constructed by combining the sulfur emissions data from Stern (2006) with data from the Penn World Tables (Heston et al., 2009) and the World Bank's World Development Indicators. The data set includes annual data on real income, investment, population, sectoral composition and sulphur emissions for 68 countries over the period 1970-2000.²⁵ I measure s as the average share of real investment in real GDP, n as the annual population growth rate, z^c as the level of sulphur emissions divided by population size, and ϕ as the value share of industrial output in GDP.

In total, five different samples are considered.²⁶ The first sample, *All*, contains the 68 countries for which data is available. The second, *Non-Oil* eliminates all OPEC members from the sample as oil extraction is the primary source of income in these countries. The third sample, *Inter.*, excludes all countries with a population less than one million and data quality grade of "D" from the Penn World Tables as measurement error is likely to be a greater problem for these countries. Samples four and five are simply decompositions of the third sample into Non-OECD and OECD countries.²⁷

4.3. Results. To test whether sulfur dioxide emissions are converging conditional on industrialization, I estimate various specifications of both equation (42) and equation (44). These estimation results are presented in Table 1 and Table 2.

Table 1 reports estimates of equations (42) and (44) using the full sample of 68 countries. Columns (1) and (2) report estimates of ACE , while columns (3) and (4) report estimates of CCE . In each case, the first specification ignores compositional changes, while the second includes the lagged value share of industrial output in GDP. These results support the theory's prediction of convergence conditional on industrialization. In all four specifications, the coefficient on lagged emissions per capita is less than one, which is consistent with convergence in per capita pollution emissions. More importantly, in columns (2) and (4), the lagged share of industrial production in GDP is statistically significant and has the

²⁵The time period and the cross-country coverage was determined by data limitations imposed by the Penn World Tables and the World Development Indicators database.

²⁶A list of the countries comprising each sample is given in the appendix.

²⁷Summary statistics for all five samples are given in the appendix.

TABLE 1. Industrialization and Convergence

Variable	(1)	(2)	(3)	(4)
$\ln z_{t-\tau}^c$	0.7817 ^a (0.0899)	0.7606 ^a (0.0945)	0.7769 ^a (0.0902)	0.7572 ^a (0.0946)
$\ln s$	-	-	0.0506 ^a (0.0175)	0.0379 ^b (0.0168)
$\ln(\delta + n + g_B)$	-	-	-0.1491 ^b (0.0743)	-0.1506 ^b (0.0707)
$\ln \phi_{t-\tau}$	-	0.1814 ^b (0.0780)	-	0.1771 ^b (0.0780)
Obs.	2040	2040	2040	2040
N	68	68	68	68
Adj. R^2	0.9677	0.9674	0.9670	0.9663

Note: ^a, ^b, and ^c indicate significance at the 1%, 5% and 10% levels respectively. In all cases, the dependent variable is the level of sulfur dioxide emissions in the current period. N refers to the number of countries in the sample. In all cases, the entire sample was used.

sign predicted by theory. This means convergence is occurring conditional on the sectoral composition of the economy. Moreover, the restriction $\beta_1 + \beta_2 = 1$ cannot be rejected in either case, providing further support for the model.

These results also provide evidence on the nature of convergence. If convergence in emissions per capita is absolute and countries are homogeneous, determinants of the balanced growth path level of income per capita should not be statistically significant. However, given columns (3) and (4), it is clear this is not the case; the coefficients on both savings and effective depreciation are statistically significant. In addition, savings and effective depreciation are the expected sign and magnitude; the restriction $\beta_3 = -\beta_4$ cannot be rejected. This indicates convergence is conditional on country specific characteristics, meaning two countries will converge to the same level of emissions per capita only if they have the same savings rate, s , and effective depreciation rate, $(\delta + n + g_B)$.

Taken together, the estimates presented in Table 1 are indicative of *CCE* as economies industrialize. To test the robustness of this finding, equation (44) is re-estimated using 4 alternative samples. These results are presented in columns (2)-(5) of Table 2. Column (2) eliminates OPEC countries, while column (3) excludes countries with a population less than one million as well as countries that received a grade of “D” from the Penn World Tables. Column (4) limits the sample from column (3) to Non-OECD countries while column (5)

TABLE 2. Conditional Convergence in Emissions

Variable	(1)	(2)	(3)	(4)	(5)
$\ln z_{t-\tau}^c$	0.7572 ^a (0.0946)	0.7432 ^a (0.1006)	0.7160 ^a (0.1129)	0.6272 ^a (0.1303)	0.9179 ^a (0.0206)
$\ln s$	0.0379 ^b (0.0168)	0.0407 ^b (0.0184)	0.0490 ^b (0.0239)	0.0714 ^b (0.0313)	0.1330 ^b (0.0487)
$\ln(\delta + n + g_B)$	-0.1506 ^b (0.0707)	-0.1376 ^c (0.0798)	-0.1612 (0.1020)	-0.1084 (0.1307)	-0.4366 ^b (0.1841)
$\ln \phi_{t-\tau}$	0.1771 ^b (0.0780)	0.1899 ^b (0.0844)	0.2425 ^b (0.1140)	0.2112 ^c (0.1093)	-0.0588 (0.0651)
Obs.	2040	1890	1560	1230	330
N	68	63	52	41	11
Adj. R^2	0.9677	0.9655	0.9621	0.9503	0.9873

Note: ^a, ^b, and ^c indicate significance at the 1%, 5% and 10% levels respectively. N refers to the number of countries in the sample. In all cases, the dependent variable is the level of sulfur dioxide emissions in the current period. Column 1 employs the entire sample. Column 2 eliminates OPEC members. Column 3 excludes OPEC members, countries with a population less than a million and countries that received a grade of D from the PWT. Columns 4 and 5 divide the sample from column 3 into Non-OECD and OECD members, respectively.

limits it to members of the OECD. For ease of comparison, column (1) restates the estimates for the full sample reported previously in Table 1.

From Table 2 it is clear that restricting the sample does not affect the results significantly. In both columns (2) and (3), the coefficient on lagged emissions per capita is less than one and statistically significant. The coefficients on the lagged value share of industrial output in GDP is also statistically significant and of the expected sign and the restriction $\beta_1 + \beta_2 = 1$ cannot be rejected in either case. In addition, the coefficient on savings is statistically significant regardless of sample. Effective depreciation is only statistically significant in column (2), but the restriction $\beta_3 = -\beta_4$ cannot be rejected cannot be reject in either specification.

The results of further dividing the sample into low-income (column (4)) and high-income (column (5)) countries are also consistent with the predictions of the theory. Given that there are diminishing returns to capital, the theory predicts changes in the composition of output will have the largest effect on pollution emission at the start of industrialization. This means compositional changes should have the largest effect in developing countries, but little to no effect when countries are highly industrialized. Hence, the finding that the

coefficient on the lagged value share of industrial output in GDP is statistically significant for Non-OECD countries (column (4)), but insignificant for OECD countries (column (5)) is unsurprising.

All together, the magnitudes and significance of the estimated coefficients on lagged pollution per capita and the lagged share of industrial production in GDP, and the significance of savings and effective depreciation indicate the model fits the data well. This suggests the process of industrialization posited here is a key driver of cross country variation in sulfur dioxide emissions.

The importance of industrialization in determining emissions can be seen clearly from column (3). These coefficient estimates indicate industrialization has a much larger effect on pollution levels than either savings or effective depreciation. For example, a 1% increase in industry's share of total output is associated with a 24.3% increase in the level of emissions per capita, whereas a 1% increase in the savings rate is only associated with a 4.9% increase in the level of emissions per capita. This suggests policies that alter the composition of production (such as industrial subsidies) will have much larger direct effects on the environment than policies that affect economic growth (such as increases in savings rates).

5. CONCLUSION

This paper presented a simple two-sector model of neoclassical growth in a small open economy to investigate the relationship between growth and environmental outcomes. Most existing research in this area has come through the lens of the EKC, but existing theories have not come to grips with three relevant features of the data: (i) there has been a great deal of cross-country convergence in pollution emissions over time, (ii) there is substantial variation in the emission intensities of industrial pollutants across both over time and across countries, and (iii) pollution abatement costs have been a small and constant fraction of GDP in the industrialized world. This paper provides a theory of growth and the environment that also explains these other features.

The theory showed how the EKC can arise during the transition from agricultural production to industrial production as economies develop. As countries develop and accumulate capital, pollution levels increase as a result of increases in the scale of production as more output is produced, and through shifts in the composition of output towards pollution intensive industrial production. Initially these increases overwhelm the pollution reducing effect of technological progress. As development proceeds and diminishing returns to capital set in, growth and compositional changes slow; as a result technological progress in abatement occurs faster than emissions growth and emissions levels fall. Such changes in scale, composition and technique as countries industrialize generate an EKC.

Although the theory showed why an EKC could arise through industrialization, it is not a necessary result. Instead the theory predicted cross country convergence in emissions as economies industrialize. To evaluate this prediction I derived an estimating equation directly from the theory by log-linearizing the model around the balanced growth path. The empirical results showed that the process of industrialization is a significant determinant of observed changes in sulfur emissions, supporting the theory's prediction: a 1% increase in industry's share of total output is associated with an 24% increase in the level of emissions per capita.

APPENDIX A. PROOFS TO PROPOSITIONS

Proposition 1. To begin, recall that the growth rate of capital,

$$(45) \quad \frac{\dot{k}}{k} = \frac{sG(p, k)}{k} - (\delta + n + g_B)$$

is the difference between two terms: the savings curve, $(s/k)G(p, k)$, and the depreciation curve, $(\delta + n + g_B)$.

Existence. Note that:

$$(46) \quad \lim_{k \rightarrow 0} \frac{G(p, k)}{k} = \lim_{k \rightarrow 0} \frac{ph(k)}{k} = \lim_{k \rightarrow 0} ph'(k) = \infty$$

where the second equality follows from L'Hopital's rule and the third follows from the Inada conditions. Similarly:

$$(47) \quad \lim_{k \rightarrow \infty} \frac{G(p, k)}{k} = \lim_{k \rightarrow \infty} \frac{(1 - \theta)f(k)}{k} = \lim_{k \rightarrow \infty} (1 - \theta)f'(k) = 0$$

Again, the second equality follows from L'Hopital's rule and the third follows from the Inada conditions. The savings curve must intersect with the depreciation curve and a balanced growth path must exist.

Uniqueness. The savings curve can be rewritten as $(G(p, k)/k) = p(h(k)/k)$ if $k \leq k_y$. Hence:

$$(48) \quad \frac{\partial(G(p, k)/k)}{\partial k} = -\frac{1}{k} \left(\frac{ph(k)}{k} - ph'(k) \right)$$

Given $ph(k)/k - ph'(k) = w > 0$, $\partial(G(p, k)/k)/\partial k < 0$. Similarly if $k \geq k_x$, the savings curve can be rewritten as $(G(p, k)/k) = (1 - \theta)(f(k)/k)$ and

$$(49) \quad \frac{\partial(G(p, k)/k)}{\partial k} = -\frac{(1 - \theta)}{k} \left(\frac{f(k)}{k} - f'(k) \right)$$

As before, $f(k)/k - f'(k) = w > 0$, so $\partial(G(p, k)/k)/\partial k < 0$. To find $\partial(G/k)/\partial k$ for $k \in (k_y, k_x)$, note that gross national product must be equal to the total wages paid to all of the factors plus the lump-sum transfer of environmental tax revenue back to consumers:

$G(p, k) = rk + w + \tau z$. Differentiating the savings curve yields:

$$(50) \quad \frac{\partial(G/k)}{\partial k} = \frac{G(p, k)}{k} \left(\frac{\partial G(p, k)}{\partial k} \frac{k}{G(p, k)} - 1 \right)$$

Note that $\partial G(p, k)/\partial k = r$ and $rk/G(p, k) < 1$, so $\partial(G(p, k)/k)/\partial k < 0$. This means $\partial(G(p, k)/k)/\partial k < 0$ for all $k > 0$ and the balanced growth path is unique.

Stability. The conditions for existence and uniqueness ensure that the savings curve only cuts the depreciation curve from above. This ensures the stability of the balanced growth path. \square

Proposition 2. To begin, note that the growth rate of aggregate emissions can be written as:

$$(51) \quad \frac{\dot{Z}}{Z} = g_z + \left(\frac{k}{k - k_y} \right) \left(\frac{\dot{k}}{k} \right)$$

where $k > k_y$ because the economy is diversified. Substituting for (\dot{k}/k) :

$$(52) \quad \frac{\dot{Z}}{Z} = g_z + \left(\frac{sG(p, k)}{k - k_y} \right) - \left(\frac{k}{k - k_y} \right) (\delta + n + g_B)$$

Differentiating yields:

$$(53) \quad \frac{\partial(\dot{Z}/Z)}{\partial k} = \frac{(sr - (\delta + n + g_B))(k - k_y) - (sG(p, k) - (\delta + n + g_B)k)}{(k - k_y)^2}$$

where $r = \partial G(p, k)/\partial k$. Along the balanced growth path, $\dot{k}/k = 0$. Given that $G(p, k) = rk + w + \eta x$, this means that on the balanced growth path:

$$(54) \quad sr - (\delta + n + g_B) = - \left(\frac{sw}{k^*} + \frac{s\eta x^*}{k^*} \right)$$

where k^* and x^* denote the fixed levels of capital and industrial output per effective worker along the balanced growth path. Substituting (54) into (53) yields:

$$(55) \quad \frac{\partial(\dot{Z}/Z)}{\partial k} = \frac{-(sw/k^* + s\eta x^*/k^*)(k - k_y) - (sG(p, k) - (\delta + n + g_B)k)}{(k - k_y)^2}$$

Given Proposition 1, if $k < k^*$, $sG(p, k) > (\delta + n + g_B)k$ and $\partial(\dot{Z}/Z)/\partial k < 0$. Thus, the growth rate of aggregate emissions is falling as capital accumulates. Moreover, suppose that the growth rate of aggregate emissions is zero. From (51), this implies:

$$(56) \quad \frac{\dot{k}}{k} = -g_z \left(\frac{k - k_y}{k} \right) > 0$$

where $g_z < 0$ by sustainability. Given the results of Proposition 1, this means $\dot{Z}/Z = 0$ for some $k < k^*$. Denote this k as k^p . Clearly, if $k_0 < k^p$, emissions peak during the transition to the balanced growth path. If instead $k_0 \geq k^p$, emissions decline monotonically as the economy approaches the balanced growth path. \square

Proposition 3. Recall that the trade pattern is determined by the level of k : if $k = \bar{k}$, trade is balanced; if $k < \bar{k}$, the economy is a net exporter of agricultural goods; and if $k > \bar{k}$ the economy is a net exporter of industrial goods. Also recall that if an EKC is generated, $k_0 < k^p < k^*$. Let $(\overline{\delta + n + g_B})$ denote the values of $(\delta + n + g_B)$, such that $k^* = \bar{k}$. If $(\delta + n + g_B) > (\overline{\delta + n + g_B})$, then $k^p < k^* < \bar{k}$. If $(\delta + n + g_B) < (\overline{\delta + n + g_B})$, then $k^p < \bar{k} < k^*$ or $\bar{k} < k^p < k^*$. \square

Proposition 4. To begin, note $\dot{\phi}(p, k(t))/\phi(p, k(t)) = \varepsilon_{\phi k}(\dot{k}(t)/k(t))$ and $\dot{G}(p, k(t))/G(p, k(t)) = \varepsilon_{Gk}(\dot{k}(t)/k(t))$ (where $\varepsilon_{\phi k}$ and ε_{Gk} denote the elasticities of composition and output). This means equation (34) can be written as:

$$(57) \quad \frac{\dot{Z}(t)}{Z(t)} = g_z + (\varepsilon_{\phi k} + \varepsilon_{Gk}) \frac{\dot{k}(t)}{k(t)}$$

Proposition 1 indicates the economy converges to the balanced growth path given any $k_0 > 0$ and fixed p . Given the above equation, this means that any two countries that differ only in their initial endowments of capital per effective worker will undergo convergence in pollution levels as they industrialize. \square

Proposition 5. Recall that the trade pattern is determined by the level of k : if $k = \bar{k}$, trade is balanced; if $k < \bar{k}$, the economy is a net exporter of agricultural goods; and if $k > \bar{k}$

the economy is a net exporter of industrial goods. Also recall that convergence in pollution levels occurs for any $k_0 < k^*$. Let $(\overline{\delta + n + g_B})$ denote the values of $(\delta + n + g_B)$, such that $k^* = \bar{k}$. If $(\delta + n + g_B) > (\overline{\delta + n + g_B})$, then $k_0 < k^* < \bar{k}$. If $(\delta + n + g_B) < (\overline{\delta + n + g_B})$, then $k_0 < \bar{k} < k^*$ or $\bar{k} < k_0 < k^*$. \square

APPENDIX B. DATA

Table 3: Summary Statistics

Variable	Sample				
	All	Non-oil	Intermediate	Non-OECD	OECD
z^c	0.0126 (0.0203)	0.0129 (0.0210)	0.0142 (0.0221)	0.0109 (0.0205)	0.0263 (0.0235)
s	0.1963 (0.1021)	0.1903 (0.0709)	0.1952 (0.0967)	0.1673 (0.0826)	0.2992 (0.0713)
$(\delta + n + g)$	0.0711 (0.0105)	0.0709 (0.0107)	0.0708 (0.0107)	0.0745 (0.0087)	0.0570 (0.0041)
ϕ	0.3029 (0.1081)	0.2939 (0.1041)	0.3082 (0.1008)	0.3023 (0.1097)	0.3301 (0.0507)
N	68	63	52	41	11

Table 4: Sample Countries

Country	All	Non-oil	Inter.	Non-OECD	OECD
1 Algeria	1	0	0	0	0
2 Argentina	1	1	1	1	0
3 Barbados	1	1	0	0	0
4 Benin	1	1	1	1	0
5 Bolivia	1	1	1	1	0
6 Botswana	1	1	1	1	0
7 Brazil	1	1	1	1	0
8 Burkina Faso	1	1	1	1	0
9 Cameroon	1	1	1	1	0
10 Canada	1	1	1	0	1
11 Central African Republic	1	1	0	0	0
12 Chile	1	1	1	1	0
13 China	1	1	1	1	0
14 Colombia	1	1	1	1	0
15 Congo, Dem. Rep.	1	1	0	0	0
16 Congo	1	1	1	1	0
17 Costa Rica	1	1	1	1	0
18 Cote d'Ivoire	1	1	1	1	0
19 Dominican Republic	1	1	1	1	0

Table 4: Sample Countries

Country	All	Non-oil	Inter.	Non-OECD	OECD
20 Ecuador	1	0	0	0	0
21 Egypt	1	1	1	1	0
22 Fiji	1	1	0	0	0
23 Finland	1	1	1	0	1
24 France	1	1	1	0	1
25 Ghana	1	1	1	1	0
26 Greece	1	1	1	0	1
27 Guatemala	1	1	1	1	0
28 Guinea-Bissau	1	1	0	0	0
29 India	1	1	1	1	0
30 Indonesia	1	0	0	0	0
31 Iran	1	0	0	0	0
32 Jamaica	1	1	1	1	0
33 Japan	1	1	1	0	1
34 Jordan	1	1	1	1	0
35 Kenya	1	1	1	1	0
36 Korea	1	1	1	0	1
37 Luxembourg	1	1	0	0	0
38 Madagascar	1	1	1	1	0
39 Malaysia	1	1	1	1	0
40 Mali	1	1	1	1	0
41 Mauritania	1	1	1	1	0
42 Mexico	1	1	1	1	0
43 Morocco	1	1	1	1	0
44 Nepal	1	1	1	1	0
45 Netherlands	1	1	1	0	1
46 Niger	1	1	0	0	0
47 Norway	1	1	1	0	1
48 Oman	1	1	1	1	0
49 Papua New Guinea	1	1	0	0	0
50 Paraguay	1	1	1	1	0
51 Peru	1	1	1	1	0
52 Philippines	1	1	1	1	0
53 Puerto Rico	1	1	0	0	0

Table 4: Sample Countries

Country	All	Non-oil	Inter.	Non-OECD	OECD
54 Senegal	1	1	1	1	0
55 South Africa	1	1	1	1	0
56 Spain	1	1	1	0	1
57 Sri Lanka	1	1	1	1	0
58 Sudan	1	1	0	0	0
59 Swaziland	1	1	1	1	0
60 Sweden	1	1	1	0	1
61 Thailand	1	1	1	1	0
62 Tunisia	1	1	1	1	0
63 Turkey	1	1	1	1	0
64 Uganda	1	1	0	0	0
65 United States	1	1	1	0	1
66 Venezuela	1	0	0	0	0
67 Zambia	1	1	1	1	0
68 Zimbabwe	1	1	1	1	0
Total	68	63	52	41	11

REFERENCES

- Aldy, Joseph E.**, “Per Capita Carbon Dioxide Emissions: Convergence or Divergence?,” *Environmental and Resource Economics*, 2006, *33*, 533–555.
- Andreoni, James and Arik Levinson**, “The simple analytics of the environmental Kuznets curve,” *Journal of Public Economics*, 2001, *80* (2), 269 – 286.
- Antweiler, Werner, Brian R. Copeland, and M. Scott Taylor**, “Is Free Trade Good For the Environment?,” *The American Economic Review*, September 2001, *91* (4), 887–908.
- Arellano, Manuel and Stephen Bond**, “Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equation,” *Review of Economic Studies*, 1991, *58* (2), 277–297.
- Barbier, Edward B.**, “Introduction to the Environmental Kuznets Curve Special Issue,” *Environment and Development Economics*, 1997, *2*, 369–381.
- Brock, William A. and M. Scott Taylor**, “The Green Solow Model,” *The Journal of Economic Growth*, 2010, *15* (2), 127–153.
- Bruvoll, Annegrete and Hege Medin**, “Factors Behind the Environmental Kuznets Curve: A Decomposition of the Changes in Air Pollution,” *Environmental and Resource Economics*, 2003, *24*, 27–48.
- Bulte, Erwin, John A. List, and Mark C. Strazicich**, “Regulatory Federalism and the Distribution of Air Pollutant Emissions,” *Journal of Regional Science*, 2007, *47* (1), 155–178.
- Caselli, Francesco, Gerardo Esquivel, and Fernando Lefort**, “Reopening the Convergence Debate: A New Look at Cross-Country Growth Empirics,” *The Journal of Economic Growth*, 1996, *1*, 363–389.
- Copeland, Brian R. and M. Scott Taylor**, “North-South Trade and the Environment,” *The Quarterly Journal of Economics*, 1994, *109* (3), 755–787.
- and ———, *Trade and the Environment: Theory and Evidence*, Princeton University Press, 2003.
- and ———, “Trade, Growth and the Environment,” *Journal of Economic Literature*, March 2004, *42*, 7–71.
- Criado, Carlos Ordas, Simone Valente, and Thanasis Stengos**, “Growth and the Pollution Convergence Hypthesis: A Nonparametric Approach,” *Journal of Environmental Economics and Management*, Forthcoming.
- Deardorff, Alan V.**, “A Geometry of Growth and Trade,” *The Canadian Journal of Economics*, 1974, *7* (2), 295–306.
- Durlauf, Steven N., Paul A. Johnson, and Jonathan R.W. Temple**, “Growth Econometrics,” in Phillipe Aghion and Steven N. Durlauf, eds., *Handbook of Economic Growth*,

Vol. 1A, Elsevier, 2005, chapter 8.

- Grossman, Gene M. and Alan B. Krueger**, “Economic Growth and the Environment,” *The Quarterly Journal of Economics*, 1995, 110 (2), 353–377.
- Harbaugh, William T., Arik Levinson, and David Molloy Wilson**, “Reexamining the Empirical Evidence for an Environmental Kuznets Curve,” *The Review of Economics and Statistics*, August 2002, 84 (3), 541–551.
- Heston, Alan, Robert Summers, and Bettina Aten**, “Penn World Table 6.3,” August 2009.
- Islam, Nazrul**, “Growth Empirics: A Panel Data Approach,” *The Quarterly Journal of Economics*, November 1995, 110 (4), 1127–1170.
- John, A. and R. Pecchenino**, “An Overlapping Generations Model of Growth and the Environment,” *The Economic Journal*, 1994, 104 (427), 1393–1410.
- Lee, Junsoo and John A. List**, “Examining Trends of Criteria Air Pollutants: Are the Effects of Governmental Intervention Transitory?,” *Environmental and Resource Economics*, 2004, 29, 21–37.
- Lopez, Ramon**, “The environment as a factor of production: The effects of economic growth and trade liberalization,” *Journal of Environmental Economics and Management*, September 1994, 27 (2), 163–184.
- Mankiw, N. Gregory, David Romer, and David N. Weil**, “A Contribution to the Empirics of Economic Growth,” *The Quarterly Journal of Economics*, May 1992, 107 (2), 407–437.
- Selden, Thomas M. and Daqing Song**, “Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions?,” *Journal of Environmental Economics and Management*, 1994, 27, 147–162.
- , **Anne S. Forrest, and James E. Lockhart**, “Analyzing the Reductions in U.S. Air Pollution Emissions: 1970 to 1990,” *Land Economics*, 1999, 75 (1), 1–21.
- Stern, David I.**, “The Rise and Fall of the Environmental Kuznets Curve,” *World Development*, 2004, 32 (8), 1419–1439.
- , “Reversal of the Trend in Global Anthropogenic Sulfur Emissions,” *Global Environmental Change*, 2006, 16, 207–220.
- **and Michael S. Common**, “Is There an Environmental Kuznets Curve for Sulfur?,” *Journal of Environmental Economics and Management*, 2001, 41 (2), 162–178.
- Stokey, Nancy L.**, “Are There Limits to Growth?,” *International Economic Review*, February 1998, 39 (1), 1–31.
- Strazicich, Mark C. and John A. List**, “Are CO₂ Emissions Levels Converging Among Industrial Countries?,” *Environmental and Resource Economics*, 2003, 24 (3), 263–271.