Richard Perkins, Eric Neumayer

Fostering environment-efficiency through transnational linkages? Trajectories of CO2 and SO2, 1980-2000

Article (Accepted version) (Refereed)

Original citation:
Perkins, Richard and Neumayer, Eric (2008) Fostering environment-efficiency through transnational linkages? Trajectories of CO2 and SO2, 1980-2000. Environment and planning A, 40 (12). pp. 2970-2989. ISSN 0308-518X

DOI: 10.1068/a4089

Fostering environment-efficiency through transnational linkages?

Trajectories of CO_2 and SO_2, 1980-2000

Revised Version

April 2008

Richard Perkins, r.m.perkins@lse.ac.uk
Eric Neumayer, e.neumayer@lse.ac.uk

Richard Perkins and Eric Neumayer

Address: Department of Geography and Environment and Centre for Environmental Policy and Governance (CEPG), London School of Economics and Political Science, Houghton Street, London WC2A 2AE, UK

Fax: +44 (0)20 7955 7412

Fostering environment-efficiency through transnational linkages? Trajectories of CO_2 and SO_2, 1980-2000

Abstract. Recent optimism about sustainability has centred on the opportunities for improvements in environment-efficiency through the international diffusion of environmentally-beneficial innovations. This paper investigates two claims about the conditions under which countries are most likely to realise these gains. First, "dirtier" economies should improve their environment-efficiency faster, as they adopt environmentally sound technologies and policies similar to those in "cleaner" countries, resulting in catch-up and convergence over time. Second, transnational linkages accelerate the international spread of environmentally-beneficial innovations, and therefore improvements in environment-efficiency. To test these claims, we use econometric techniques to examine the dynamics and determinants of two pollutants, CO_2 and SO_2, using a panel comprising up to 114 countries over the period 1980-2000. Our empirical findings broadly support both claims. Applying tests of unconditional convergence, we find robust evidence for convergence in levels of CO_2 and SO_2-efficiency, indicating catch-up by less pollution-efficient economies over time. Similarly, confirming claims about transnational linkages, we find that imports from more pollution-efficient countries and telecommunications connectivity are associated with faster improvements in domestic CO_2 and SO_2-efficiency. Results also suggest that inward FDI stock is positively associated with CO_2-efficiency. Yet we find that exports to countries with high levels of pollution-efficiency have no discernable effect on domestic pollution-efficiency.

Introduction

A central theme of ecological modernisation discourse is the idea that countries can achieve more ecologically "sustainable" growth by improving the environment-efficiency[1] of production and consumption. Improvements in environment-efficiency allow countries to achieve "more from less", thereby potentially counteracting the scale effect from economic growth (WCED, 1987; Weizsäcker et al., 1998). Indeed, precisely for this reason, optimism about tackling global environmental problems such as climate change has centred on the opportunities to raise environment-efficiency. Our goal in the present paper is to empirically investigate two claims about the conditions under which countries are likely to realise these gains through the diffusion of environmentally-beneficial innovations.

The first is that "dirtier" economies should be able to improve their environment-efficiency faster than "cleaner" ones. Specifically, through the international transfer and adoption of environmentally sound technologies[2] (ESTs) and policies, less pollution-efficient countries are well-placed to catch-up in terms of environment-efficiency with their more pollution-efficient counterparts (Mielnik and Goldemberg, 2000). We should, in other words, expect cross-national convergence in pollution-efficiency over time.[3]

A second claim is that a country's environment-efficiency will be influenced by its connections with other countries, with transnational linkages accelerating improvements in

[1] We define environment-efficiency as economic output produced/consumed for any given use of the environment as a source or sink.

[2] We define ESTs as any technological innovation which reduces the pollution-intensity of economic activity, including: end-of-pipe technologies, clean process technologies and/or less pollution-intensive energy types.

[3] We use the terms environment-efficiency, emissions-efficiency and pollution-efficiency interchangeably throughout the text.

domestic pollution-efficiency. Such suggestions have typically been made in relation to trade and investment linkages, which are said to increase the supply and demand for ESTs (OECD, 1998; Wallace, 1996). More recently, however, similar arguments have been made about the spread of environmentally-beneficial policy innovations (Garcia-Johnson, 2000; Rock, 2002; Vogel, 2000).

Unfortunately, existing empirical work has done a poor job of empirically scrutinising either of these claims. Therefore, with a view to advancing current understanding, the present paper uses large sample, econometric estimation techniques to examine whether: (1) there is evidence of less environment-efficient countries catching-up with more pollution-efficient ones, i.e. convergence over time; and (2) countries' transnational linkages – via trade, investment and telecommunications – influence the rate at which they improve domestic pollution-efficiency.

Our study advances on previous empirical work in four important ways. First, our sample includes a far larger number of countries (up to 114), comprising the majority of the world's economies and capturing nearly 90 per cent of the global population (see appendix 2). By contrast, past work has typically focused on a sub-set of developed and/or developing countries, and therefore potentially suffers from selection bias (Hilton, 2001; IEA, 1994; Markandya et al., 2006; Mielnik and Goldemberg, 2000). Second, we deploy more sophisticated measures to examine the influence of a country's trading partners on domestic environment-efficiency. Invariably, past studies have taken general trade flows and/or openness to capture efficiency enhancing spillover effects, ignoring differences in the level of environment-efficiency in trading partners (Reppelin-Hill, 1999). Conversely, we use both import and export variables that account for levels of pollution-efficiency in countries with which a particular economy is linked via trade, and restrict our focus to goods that are likely to strongly influence domestic pollution-efficiency. Third, we go beyond existing studies in our conceptualisation of transnational linkages. As well as trade and investment, our study considers the influence of a country's transnational telecommunications connectivity. The importance of international communications has begun to receive growing recognition in the literature on technological diffusion (Gong and Keller, 2003; Wong, 2004) and cross-border investment flows (Portes and Rey, 2005). Uniquely, our study investigates their role in catalysing improvements in pollution-efficiency.

Fourth, we focus on two pollutants, carbon dioxide (CO_2) and sulphur dioxide (SO_2). The norm for past studies is one (Hilton, 2001; Mielnik and Goldemberg, 2000). We selected these pollutants since they are key sources of environmental damage and therefore indicators of the extent to which countries have decoupled economy from environment. Carbon dioxide is the leading contributor to anthropogenic global warming; while sulphur dioxide is a major cause of ecosystem acidification (but, as explained later, also potentially counteracts the radiative effect of CO_2). Another reason for selecting these pollutants is that data exist on national emissions of CO_2 and SO_2, both for a large number of countries and years, whereas for other pollutants no such data with wide country and temporal coverage exist.

We also concentrate on both CO_2 and SO_2 since they differ across a number of important dimensions. SO_2 is a characteristic "first generation" pollutant (Graham, 1999), in that a large share of emissions derive from point sources, are comparatively cheap to abate through end-of-pipe technologies and involve potentially costly, short-term impacts. Conversely, CO_2 is a stereotypical "second generation" environmental problem. Emissions originate from a large number of diffuse sources, are potentially difficult and costly to abate and involve impacts that are geographically and temporally dispersed.

Important differences also exist in the incentives to abate CO_2 and SO_2. First off, the gases differ in the relative importance of market versus regulatory drivers. The impetus to cut CO_2 has historically derived almost exclusively from non-environmental market pressures, and specifically, the drive to reduce energy costs amongst producers and/or consumers. Market driven technological change has similarly played an important role in reducing SO_2 emissions through process-integrated improvements. However, because abating sulphur does not always contribute to improved competitiveness, environmental regulations have also assumed considerable significance in compelling firms to reduce SO_2 emissions – either through investments in end-of-pipe equipment, "clean" process technologies and/or switching to less sulphur-intensive fuels (Popp, 2006; Taylor et al., 2005).

Furthermore, the incentive to "free ride" off other countries' domestic abatement efforts differs. SO_2 is a regional (transboundary) pollutant characterised by an asymmetric problem structure. That is, the environmental impacts experienced by a particular country from SO_2 emissions are not equal, but vary according to its own emissions and those of its geographically proximate neighbours (Murdoch and Sandler, 1997). Conversely, CO_2 is a truly global (transboundary) pollutant, characterised by greater symmetry amongst countries. Although predicted to vary, with developing countries bearing a disproportionate burden, the negative environmental consequences from CO_2 emissions are likely to be more evenly distributed at the global level (IPCC, 2007). In principle, to the extent that emission reductions are a public good, there are incentives for countries to free ride off cuts in both CO_2 and SO_2 emissions made by other states. Yet, as discussed later, the regional and asymmetrical characteristics of SO_2 suggest that domestic abatement effort is likely to be far more strongly influenced by the actions of geographical neighbours.

The rest of the paper is structured as follows. Section 2 explores the conceptual foundations for convergence in pollution-efficiency. Section 3 discusses claims about the role of international trade, investment and telecommunications connectivity in accelerating improvements in environment-efficiency. Section 4 outlines the findings of past empirical work. Section 5 details our research design while results are presented in section 6. Finally, section 7 concludes and discusses the wider implications of our findings.

Conceptualising convergence in environment-efficiency

Why should we expect catch-up and, by implication, convergence in environment-efficiency? According to the literature, there are two possible mechanisms. The first involves the international spread of technology (Mielnik and Goldemberg, 2002). Technology is widely recognised as a central determinant of the pollution-intensity of a country's consumption and production activities (Weizsäcker et al., 1998). Technological progress means that many modern technologies used in (potentially) energy- and/or resource-intensive applications are often considerably less environment-intensive than their vintage counterparts. As these designs and configurations diffuse – i.e. "spillover" – from more to less technologically advanced countries, and their installed technological base becomes more similar, so it follows that the pollution-efficiencies of national economies should converge.

Indeed, international technological spillovers – embodied in physical equipment and disembodied as technological know-how – have long been theorised as a central mechanism in economic models of convergence, which predict catch-up in income levels over time (Gong and Keller, 2003). Central to this hypothesised process of catch-up is the existence of transnational networks connecting geographically dispersed countries. Through transnational linkages, countries can take advantage of technologies developed in more advanced economies, allowing indigenous firms to leapfrog decades of potentially costly technological effort (Wong, 2004). Additionally, transnational linkages are hypothesised to transmit price effects, with less efficient firms investing in more modern, productive technologies in order to compete in product markets with high efficiency foreign competitors.

Similar arguments have been advanced in relation to environmental performance and efficiency. Engagement with other countries via transnational networks is said to expand the domestic availability of ESTs, as well as enhance the demand for more modern, efficient technologies (Grubb et al., 2002; Reppelin-Hill, 1999; Rock, 2002; Warhurst and Bridge, 1997). Pollution-inefficient countries should therefore catch-up as they invest in environment-efficient technologies similar to those deployed in more environment-efficient economies. Typically, such claims have been made for developing countries, although they are equally relevant to lagging, environment-inefficient developed ones (Markandya et al., 2006).

Whether developed or developing, however, as countries approach the technological frontier, so their ability to secure further improvements in pollution-efficiency will inevitably decline. The latest technologies do not benefit from learning investments. They are therefore frequently more costly, unreliable and risky, characteristics which reduce their uptake by potential adopters. The result: the rate of catch-up should decline as countries improve their pollution-efficiency over time.

A second mechanism of catch-up centres on the geographic spread of similar policy ideas, instruments and regulatory approaches (Tews et al., 2003). This may involve non-environmental policy developments with positive environmental consequences (Grubb et al., 2002). More directly, convergence may arise from the spread of environmental policies, which compel actors in different countries to achieve similar environmental performances (Hilton, 2001). Hence countries can sign-up to regional and/or global treaties, obligating signatories to comply with restrictions governing their environmental behaviour (Tews et al., 2003). Alternatively, policies may diffuse horizontally, spreading from high-regulating states to low-regulating ones. Indeed, there is anecdotal evidence that, following the lead of developed countries, a growing number of developing ones are now adopting standards governing SO_2 (Couch, 1999; Rock, 2002).

Of course, cross-national convergence in environment-efficiency does not necessarily imply ecologically "sustainable" outcomes. What ultimately matters for sustainability is the extent to which improvements in environment-efficiency (i.e. "technique") offset the effects of continued economic growth (i.e. "scale"). For CO_2, models suggest that economic growth is likely to lead to rapidly rising emissions over the coming century, with potentially catastrophic consequences for climate stability (IPCC, 2007). It is beyond the scope of the present study to empirically investigate the net outcome of scale and technique effects. We simply note here that convergence in environment-efficiency might be expected to slow the rate of CO_2 emissions growth. In the case of SO_2, convergence may also slow emissions growth in some countries and accelerate reductions in others. Paradoxically, however, this may aggravate anthropogenic warming, in that sulphate aerosols are believed to have an indirect cooling effect.

The role of transnational linkages

A unifying feature of the above accounts is the functional importance ascribed to various transnational linkages. Foremost amongst these linkages identified in the existing literature are international trade and investment (OECD, 1998). In the next two sub-sections, we examine their hypothesised role in improving environment-efficiency, before going on to consider other possible transnational linkages.

(a) Trade

The argument that international trade creates favourable conditions for raising environment-efficiency rests chiefly on their role in accelerating the diffusion of ESTs. Directly, imports allow domestic actors to acquire new and/or cheaper ESTs, and indirectly, may increase the supply of new technology via knowledge spillovers. Exports may also engender knowledge spillovers as indigenous firms learn from foreign competitors about ways to improve process and/or product technologies in the direction of greater environment-efficiency (Chuang, 2002). Further, by exposing indigenous firms to greater competition, trade flows potentially provide an impetus for investments in modern, efficient technologies with higher levels of embodied environmental performance (OECD, 1998).

Import and export linkages are additionally thought to accelerate the diffusion of environmental policies from high-regulating states to low-regulating ones (Vogel, 2000). Trade ties facilitate cross-border learning about the existence, benefits and legitimacy of environmental policy interventions, providing the foundations for emulative dynamics. They also expose countries to enhanced international scrutiny regarding their domestic environmental performance, and possibly, coercive environmental pressures from more powerful trading partners (Falkner, 2006; Frank et al., 2000; Tews et al., 2003; Vogel, 2000). In doing so, it is suggested that imports and exports potentially foster "upwards" environmental policy convergence amongst trading partners.

Yet the positive contribution of trade is unlikely to be automatic. In reality, there are two factors that might be expected to determine the extent to which trade ties influence domestic environment-efficiency (Chuang, 2002). The first is the identity of the trading partner. Import and export ties with economies characterised by high levels of environment-efficiency are more likely to lead to improvements in domestic pollution-efficiency (c.f. Coe et al., 1997; Wong, 2004). Another relevant factor determining the environmental impact of trade ties is the nature of the traded good, with certain imports/exports likely to have a far greater potential influence on environment-efficiency. Included here are (i) capital goods involved in the production of potentially pollution-intensive goods and (ii) intermediate and/or final goods whose production and/or consumption is potentially pollution-intensive.

(b) Investment

A second transnational economic linkage widely theorised to accelerate the cross-national transfer and diffusion of ESTs is foreign direct investment (FDI). As generators, owners and users of many of the world's most advanced technologies, transnational corporations (TNCs) are assumed to play a lead role in efficiency enhancing investments (Mielnik and Goldemberg, 2002). TNCs may introduce more modern ESTs to host economies directly through investments in subsidiaries, joint ventures and affiliates, or else, vending their proprietary technologies to domestic consumers and producers (OECD, 1998). Additionally, FDI may generate environmentally beneficial technological spillovers, as well as raise environment-efficiency through competitive dynamics. Furthermore, it is suggested that "green" procurement requirements imposed by TNCs on domestic suppliers may create supply chain pressures for the adoption of beyond-compliance (voluntary) environmental codes, standards and management practices (Neumayer and Perkins, 2003).

Again, the impact of each unit of inward investment is unlikely to be homogenous. Thus, investments in environment-intensive sectors of the economy should plausibly have a far greater impact on domestic pollution-efficiency than those made in comparatively unpolluting economic sectors. Compared to imports, however, the identity of the foreign investor is likely to be less pivotal. The majority of FDI originates in developed economies where levels of technical efficiency and regulatory standards are invariably comparatively high. Hence it follows that FDI should, by and large, embody positive environmental spillovers.

(c) Communications

While much of the literature on environmental convergence has defined transnational linkages narrowly in terms of trade and investment, this conception is at odds with the mainstream literature on globalisation. This emphasises the myriad of economic, political and social-cultural linkages that comprise globalisation, and moreover, their role in shaping distanciated geographies (Murray, 2006). In the present paper, we focus on one such transnational linkage that has received growing attention: international telecommunications (Gong and Keller, 2003; Portes and Rey, 2005; Wong, 2004).

The most obvious way in which international telecommunications linkages could accelerate the diffusion of ESTs – and therefore "upwards" convergence in environment-efficiency – is by facilitating cross-country learning about the availability, cost and performance of new technologies. Through telephone calls and web surfing, firms might come to learn about potentially profitable ESTs. Indeed, to the extent that information is a major impediment to the adoption of ESTs, telecommunications linkages should plausibly accelerate their geographic spread. Telecommunications could also facilitate the flow of disembodied technical knowledge (Wong, 2004). Telephone calls with foreign customers, consultants and competitors may provide domestic firms with new ideas about how to improve, for example, the energy-efficiency of production processes.

At a more general level, remote communications with other countries might foster the domestic internalisation of global norms of environmentalism. As citizens come to learn about environmentalism in other countries, so they may become socialised into accepting environmental protection as a legitimate goal (Frank et al., 2000). International communications flows might also support domestic learning about external environmental regulatory developments, raising domestic expectations regarding the "appropriate" level of environmental policy (Falkner, 2006). Transnational benchmarking of this sort has frequently been deployed by environmental non-governmental organisations in lobbying governments for more stringent environmental policy (Mason, 2005). However, similar processes are likely to operate amongst the wider public as they learn via communications from their overseas peers about stronger levels of environmental commitment, and create political demand for similar environmental policies.

Of course, implicit in the above discussion is the idea that it is not only the volume of transnational traffic that should matter, but also with whom a country communicates. It follows that communications with highly pollution-efficient countries are likely to have a positive impact on domestic pollution-efficiency, as actors learn from, and moreover, emulate their environmentally progressive peers. Conversely, communicating with actors in countries characterised by low levels of pollution-efficiency is unlikely to spillover into improved levels of domestic pollution-efficiency, although neither is it likely to retard efficiency gains.

Existing research: emissions, technology and regulation

Past empirical studies have only provided partial support for either of the above claims. On the question of catch-up, a number of authors have found evidence for cross-national convergence in energy-intensity (IEA, 1994; Lindmark, 2004; Markandya et al., 2006; Mielnik and Goldemberg, 2000). Along similar lines, Hilton (2001) finds evidence that late industrialising (i.e. developing) countries adopt environmental policy measures at lower levels of income than industrialised (i.e. developed) economies did in the past. Yet none of these studies directly examine catch-up and convergence in pollution-efficiency or derive their results from a large sample of both developed and developing countries.

Likewise, evidence linking trade and investment to improved pollution-efficiency is limited. Several studies generally show that countries more open to trade diffuse modern technologies more rapidly (Gruber, 1998; Perkins and Neumayer, 2005; Reppelin-Hill, 1999), although these works fail to explore the implications for countries' environment-efficiency. Conversely, systematic evidence linking FDI with the more rapid adoption of ESTs is sparse, with the majority of studies finding little or no effect from the presence of TNCs (Andonova, 2003; Perkins and Neumayer, 2005). More directly, Mielnik and Goldemberg (2002) find that countries with higher levels of FDI have reduced their energy-intensity faster, albeit using a bivariate correlation without control variables and a sample of only 20 states.

A number of studies have found that transnational linkages via trade and investment have been associated with the adoption of new and/or more stringent government regulatory policies (Garcia-Johnson, 2000) and private regulatory codes (Neumayer and Perkins, 2003). Yet, in stark contrast to trade and investment, the role of telecommunications in accelerating the diffusion of ESTs, environmental policies and norms has been neglected in the existing literature. Wong (2004) finds evidence that telephone voice calls with more productive countries increases domestic levels of productivity; while Neumayer and Perkins (2005) find that countries with a higher density of telephones have more ISO 9000 certificates, a productivity enhancing quality management system standard. To our knowledge, however, no quantitative studies have examined the role of telecommunications specifically in relation to ESTs, policies or environment-efficiency.

With a view to providing a more relevant, generalisable and robust test of claims about convergence and transnational linkages, the present study uses data on CO_2 and SO_2-efficiency for up to 114 countries over the period 1980-2000. We adopt a two-staged analytical approach. In the first, we apply a β-convergence cross-sectional regression model, while in the second we use a fixed effects regression model to estimate the role of trade, investment and telecommunications linkages. Further details about our research design are provided in the next section.

Research design

(a) Estimation strategy

We begin our empirical investigation by analysing what the economic literature on income convergence terms absolute or unconditional convergence (e.g. see Islam (2003); Barro and Sala-i-Martin (2004)). Countries are said to be absolutely or unconditionally converging in a variable y if over a longer span of time, and without conditioning on a set of other explanatory variables, countries with higher initial levels of y experience slower growth in y than countries with lower initial levels of y. Formally, one can test for unconditional convergence by estimating the following regression equation:

$$\text{growth in } y \text{ over total period} = \alpha + \beta \cdot \ln(\text{initial level of } y) + u$$

This test is commonly known as β-convergence. A negative β that is statistically significantly different from zero would indicate convergence. We also briefly report the change in the standard deviation of the natural logs of pollution-efficiency. Also known as σ-convergence, this measures the spread of the distribution of a variable.

In order to analyse the impact of transnational linkages on the rate of change in countries' pollution-efficiency, we switch from a simple cross-sectional analysis to a panel data model, which allows us to control for country fixed effects. Formally, we use the following model (*i* stands for country, *t* for time):

$$(1) \qquad (\ln[y_{it}] - \ln[y_{it-1}]) = \alpha + \beta_1 x_{it} + \beta_2 \ln[y_{it-1}] + a_i F_i + \text{year}_t + u_{it,}$$

where $\ln[y_{it}] - \ln[y_{it-1}]$ is growth in pollution-efficiency, or, equivalently,

(2) $$\ln[y_{it}] = \alpha + \beta_1 x_{it} + (\beta_2+1)\ln[y_{it-1}] + a_i F_i + \text{year}_t + u_{it,}$$

In practice, we estimate equation (2). The dependent variable is thus pollution-efficiency, i.e. GDP divided by emissions. The x_{it} contain our explanatory transnational linkage variables, described below, as well as control variables. Lagged pollution-efficiency is included as a further control variable. One would expect countries with lower levels of pollution-efficiency to improve their efficiency faster than countries with higher levels of pollution-efficiency. This should carry over into conditional convergence where conditional means that other explanatory variables are included. The F_i contain N-1 country dummy variables. Their inclusion is important because country-specific factors that are invariant over time – or close to invariant – could possibly impact on pollution-efficiency and be correlated with our explanatory variables. If not controlled for, this would bias our results. The year-specific dummy variables year_t capture general global trends in emissions efficiency over time. The u_{it} is a stochastic error term.

We estimate the model with Arellano and Bond's (1991) dynamic generalized method of moments (GMM) instrumental variables estimator with robust standard errors. This estimator works by first-differencing equation (2), which eliminates the F_i fixed effects, and by using past levels of the lagged dependent variable, along with the endogenous variables lagged by two or more periods, as instruments. First-order autocorrelation in the original data is unproblematic, but the estimator depends on the assumption of no second-order autocorrelation in the first-differenced idiosyncratic errors. This assumption can be tested and the test results fail to reject it (see below). The Arellano and Bond estimator has the important advantage that the spatial lag variables can be explicitly specified as endogenous, i.e. their past and contemporaneous values are allowed to be correlated with the error terms.

(b) Dependent variables

Our dependent variables are growth over the entire period 1980-2000 in emissions-efficiency of CO_2 and SO_2, i.e. the growth in GDP per unit of CO_2 and SO_2 for the cross-sectional convergence analysis. For the panel data analysis, the dependent variable is pollution-efficiency. Data on CO_2 emissions and GDP per capita in purchasing power parity are taken from IEA (2005), and data on SO_2 emissions from Stern (n.d.). We use GDP on a purchasing power parity (PPP) basis rather than the more conventional GDP at exchange rates, since the latter is well-known to understate the purchasing power of currencies in low-income economies. Appendix 1 provides summary descriptive statistics for all variables.

(c) Key explanatory variables

To capture the influence of trade linkages, we focus on the spillover effect of ESTs, policies and levels of environment-efficiency in countries with which a particular economy is linked through imports and exports of (potentially) polluting goods. Our specific variables are the lagged emissions-efficiency of trading partners from which a particular economy imports and to which it exports its machinery and manufactured goods, weighted by the relative import/export share of the trading partner in the domestic country's total machinery and manufactured imports/exports.[4] In essence, our measures comprise a spatial lag or spatial autoregressive model, which has recently become popular among social scientists in investigating the international diffusion of

[4] The lagged foreign emissions-efficiency is used because estimating a model using its contemporaneous value renders model estimation extremely difficult, given that countries would affect and be affected by other countries' emissions-efficiency simultaneously (Beck *et al.* 2006). Even conceptually, it makes more sense to use the lag because machinery and manufacturing imports are likely to embody lagged rather than contemporaneous emissions-efficiency of the exporting country.

technological, regulatory and organisational innovations (e.g. see Perkins and Neumayer (2004), Simmons and Elkins (2004) and Beck *et al.* (2006)). In the present paper, the pollution-efficiencies of countries are linked with each other – in effect, allowing environment-efficiency in one country to spillover into another one – via a transformation mechanism represented by a connectivity matrix. In our case, the matrix is given by bilateral machinery and manufactured goods import and export shares, with data taken from UN (2006). Owing to the high correlation coefficients between the two trade measures (.55 and .73 for CO_2 and SO_2, respectively), we include the import measure, for which we have a stronger theoretical expectation, once on its own before including both imports and exports together in a separate estimation.

The rationale for our particular trade measures is two-fold. First, we only want to measure the efficiency spillover effect associated with imports and exports that might have a substantive influence on domestic CO_2 and SO_2-efficiency. Manufactures are important in this respect since their production is often comparatively environment-intensive. Increased price and/or quality competition – either from imports or foreign competition in export markets – might bring about improvements in domestic environment-efficiency as indigenous firms invest in more modern, efficient production (and/or product) technologies. The importance of manufactured goods – and particularly imported ones – also potentially derives from their in-use performance. To take one example: products such as cars imported from more environment-efficient economies should have a positive impact on domestic environment-efficiency. The same goes for foreign capital goods embodying high levels of environmental performance. Indirectly, imports of machinery may also lead to efficiency enhancing knowledge spillovers, as indigenous firms appropriate foreign knowledge required to acquire, implement and possibly produce ESTs (Coe et al., 1997). Exporters of machinery might similarly engage in learning, although the case for knowledge spillovers via imports is stronger.

A second reason for our distinctive trade measures is the need to discriminate between levels of technology and/or environment-relevant policies in the partner country. A low level of pollution-efficiency is likely to indicate a more environment-inefficient technological base, lax environmental standards and/or policies that indirectly encourage pollution. Hence import and export linkages with such countries are unlikely to bring about significant improvements in pollution-efficiency in the receiving economy. Conversely, machinery and manufacturing imports from and, to a lesser extent, exports to, pollution-efficient economies are more likely to generate positive environmental spillovers, particularly via price effects and embodied technical efficiency.

Unfortunately, we cannot apply a similarly sophisticated measure for foreign direct investment. Comprehensive data exists for neither bilateral flows nor the sectoral allocation of FDI – at least for a large sample of countries. In their absence, we fall back on a simple aggregate measure, namely, cumulative stock of inward foreign direct investment relative to GDP (using data taken from UNCTAD (2004)). We measure the influence of FDI using the stock rather than volatile annual FDI inflows.

Our third explanatory variable is a measure of telecommunications connectivity and seeks to capture a country's communication openness and international linkages. As with FDI, a lack of comprehensive bi-lateral data on telephone calls and internet traffic means that it is not possible to construct a spatial lag variable. Instead, we measure a country's telecommunications linkages using the first principal component of two variables: the number of internet users per capita and international outgoing telephone traffic (in minutes) per capita[5], using data from World Bank

[5] The first principal component captures 69% of variation in the variables. Owing to limited data availability, we are forced to omit incoming calls.

(2005) and ITU (2003). While our measure does not account for differences in the pollution-efficiency of economies with which a particular country communicates, it seems implausible that telecommunications flows should involve negative environmental spillovers.

(d) Control variables

As well as our main explanatory variables, we specify two general control variables for both CO_2 and SO_2, as well as a further set of specific control variables for SO_2. The first general control variable is GDP per capita in PPP, using data from IEA (2005). We include per capita income as a proxy for several features of a country's economy, politics and society which might plausibly shape domestic environmental quality. These include popular demand for environmental protection, as well as the ability of governments to supply this demand through the enactment and enforcement of environmental policy, both of which are likely to grow as countries become richer (Grossman and Krueger, 1995). They also include the capabilities of firms to purchase, implement and operate capital-intensive ESTs (Lall, 1992). Although we would have ideally preferred to capture such dynamics directly, appropriate proxies with sufficient spatial and temporal coverage simply do not exist. Yet we believe that per capita income is sufficiently correlated with these dynamics such that its inclusion reduces potential omitted variable bias (e.g. see Dasgupta et al., 2001).

Our second general control variable is the share of industry in total value added. Industry – mining, manufacturing, construction, electricity, water and gas – is a leading source of CO_2 and SO_2 emissions. All things equal, a more industry-intensive economy will have a lower CO_2 and SO_2-efficiency. Hence we seek to control for the contribution of industry in order to ensure that our estimations do not simply pick up a (potentially misleading) structural effect, i.e. shifts in the composition of the economy over time.

For SO_2, we include two further sets of control variables in separate estimations. First, we control for the potential effect of multilateral environmental agreements on SO_2 emissions-efficiency during our period of study.[6] These comprise two agreements, the 1985 Helsinki Protocol and the 1994 Oslo Protocol, covering various European and Northern American states. The Helsinki Protocol required all signatories to reduce emissions by 30%, whereas the Oslo Protocol imposed differentiated obligations on parties. We include two variables measuring the natural log of the number of years since a country has signed the Helsinki or Oslo Protocols if it is a signatory, and zero otherwise, to account for the fact that the Protocols should have an effect that is increasing over time, but at a decreasing rate.

Second, we control for levels of SO_2 emissions in contiguous countries. Levels of acid deposition from SO_2 in one country will be influenced by emissions in neighbouring countries, together with the location of these countries and prevailing wind patterns. An important consequence of this – combined with the potentially high costs of abating sulphur – is that any one country will have an incentive to act strategically in relation to emissions from its neighbouring countries. Murdoch and Sandler (1997) theorise these dynamics in terms of an acid rain game, whereby emission reductions in neighbouring countries generate positive externalities, inducing a country to reduce its own emissions by less than it otherwise would. Unfortunately, formally modelling these strategic responses convincingly requires knowledge of the so-called transport matrix, which shows the percentage of country A's emissions which is "exported" into neighbouring countries and which percentage of country's A pollution load is "imported" from other countries. To our knowledge, no such matrix exists for a global sample, and creating one is

[6] We ignore the Kyoto Protocol for CO_2 because its emission reduction period (2008-12) is beyond the end year of our study.

far beyond the scope of our paper. In the absence of these data, we proxy the strategic response of individual states by including the log of the average level of SO_2 emissions of contiguous countries, i.e. of countries that share a common land border or are separated by a sea distance of less than 150 miles.

Results

We start with table 1, which reports tests of β-convergence over the period 1980-2000 in CO_2 and SO_2-efficiency. The first column presents convergence results for CO_2-efficiency in the full sample (developed and developing countries), while the second column provides results for the developing countries only sample, based on the standard World Bank classification. The third and fourth columns repeat the analysis for SO_2-efficiency convergence. Period growth in efficiency is regressed on the log of initial efficiency in 1980. For both pollutants and samples, the coefficients of the log of the emissions-efficiency in 1980 are negative and statistically significantly different from zero, indicating that less pollution-efficient countries are catching-up with more pollution-efficient ones. These results are confirmed by looking at σ-convergence. The full sample standard deviations of the natural log of CO_2 and SO_2-efficiency decrease from 0.88 and 1.65 in 1980 to 0.78 and 1.43 in 2000, respectively. In the developing countries sample, the respective decrease is from 0.95 to 0.85 in the CO_2, and from 1.41 to 1.23 in the SO_2 case.

The speed of convergence can be estimated by $-(\ln(\beta+1)/T)$, where T is the number of years of the study period. In the global samples, the estimated rate of convergence is around 1.9 per cent per annum for CO_2 and approximately 3.6 per cent per annum for SO_2-efficiency, respectively.[7] These are moderate rates of convergence. However, it is interesting to note that SO_2-efficiency converges faster. Most likely, this reflects the lower costs and/or difficulty of cutting SO_2 emissions, which can be readily abated from major point sources through end-of-pipe technologies and/or fuel switching. Additionally, it may reflect the high and tangible costs of acid deposition, and the comparatively rapid spread of SO_2 emission standards across a range of developed and developing countries over recent decades. The exclusion of developed countries from the sample does not greatly change the estimated speeds of convergence (1.6 and 3.1 per cent per annum, respectively), indicating that our findings are not simply driven by developed economies.

< Insert Tables 1 and 2 around here >

We now address the more interesting question of what, besides its lagged level, determines emissions-efficiency. Tables 2 and 3 show our Arellano and Bond (1991) GMM instrumental variables estimation results for CO_2 and SO_2, respectively. The first two columns of each table present results for the full sample (developed and developing countries), while columns 3 and 4 provide results for the developing countries only sample. In table 3, the additional last two columns 5 and 6 repeat the full sample analysis for SO_2, but adding the Protocol and contiguous country control variables.

With one exception, the coefficient for our import variable is positive and statistically significant in the case of both air pollutants. In other words, countries which obtain a larger share of their manufactures and machinery imports from economies with high levels of CO_2 and SO_2-efficiency experience faster improvements in domestic pollution-efficiency for these pollutants.

[7] This means that 1.9 and 3.6 per cent of the gap between a typical environment-efficient and a typical environment-inefficient country is eliminated in one year, respectively. If maintained, this rate of convergence would imply that half of the gap is eliminated in 36 and 19 years, respectively.

The result is similar for the full and developing country sub-sample. The only anomalous result is for SO_2, notably when the export variable is simultaneously included, which might suggest multicollinearity problems.

Yet exports do not have a similar effect on environment-efficiency. Countries which send a larger share of their manufactures and machinery exports to economies with high levels of CO_2 and SO_2-efficiency do not improve their domestic emissions-efficiency any faster. Although failing to confirm recent claims about the role of export markets in "trading-up" (Vogel, 2000), the discrepancy might reflect the fact that the potential mechanisms whereby high levels of environment-efficiency in trading partners spillover into the domestic economy are more numerous and diverse in the case of imports. To take one example: while imports of advanced capital goods are likely to be a central vehicle for raising domestic environment-efficiency, no equivalent mechanism exists for exports. What is more, the influence of imports on domestic environment-efficiency is likely to be more widespread. Thus, efficiency enhancing knowledge spillovers from exports are only likely to accrue to domestic exporters in the short- to medium-term, whereas spillovers from imports might be available to a far wider set of domestic actors.

A higher inward FDI stock is associated with higher CO_2-efficiency. In column 4 of table 2, this variable becomes insignificant, but only very marginally so (p-value of 0.111). Yet inward FDI has no effect on SO_2-efficiency. The most likely explanation for these differences between the two pollutants lies in their respective sources. As detailed earlier, CO_2 is more of a diffuse pollutant, originating from a diverse set of actors, applications and processes. Irrespective of the sector(s), investments by TNCs are therefore likely to impact on domestic levels of CO_2-efficiency. Conversely, the majority of anthropogenic SO_2 emissions originate from a single source, electricity generation, meaning that only FDI in this sector is likely to have a substantive influence on emissions. And because investments by transnational corporations in the electricity sector have generally remained small, our finding for SO_2 is perhaps unsurprising.

Uniquely, we find evidence that international communications linkages act as a catalyst for improvements in countries' pollution-efficiency. The estimated coefficient for the telecommunications connectivity variable is positive and statistically significant throughout for SO_2-efficiency. For CO_2-efficiency, however, it is only significant in the full sample. It may be that the influence of telecommunications connectivity in developing countries primarily operates by accelerating the downloading of more stringent regulations from high-regulating states – something which is likely to have a negligible impact in the case of CO_2 given that few states had adopted emission reduction targets similar to those for SO_2 during our period of study.

Moving to our control variables, the picture is mixed. The industry value added coefficient is statistically significant for CO_2 in both samples with the expected negative coefficient sign (marginally insignificant in column 3), but for SO_2, it is only significant in the developing country sample. The coefficient for GDP per capita is significant for CO_2. Yet it is only significant with the expected positive coefficient sign for SO_2 in three of the six estimations. Of note, GDP per capita becomes clearly insignificant if the Helsinki and Oslo Protocol variables are added to the full sample. Only relatively rich countries have signed these Protocols, such that our regulatory variables are likely to pick up some of the effect of the wealth differential among countries, rendering the GDP p.c. variable insignificant. The Helsinki Protocol variable has a positive and significant coefficient, suggesting that signatories of this Protocol have raised their emission-efficiency faster, whereas the Oslo Protocol has had no significant impact.[8] Consistent with game theory, higher emissions in foreign contiguous countries raise domestic SO_2-efficiency.

Finally, it is worth noting that we again find evidence of (this time, conditional) convergence: conditional on the fixed effects and the other explanatory variables, the coefficient of the lagged dependent variable for CO_2 and SO_2-efficiency minus one is statistically significantly negative throughout.[9]

Conclusions and discussion

While globalisation has been widely blamed for environmental degradation at a range of scales, advocates of ecological modernisation have nevertheless suggested that it may involve potential benefits. Central to this belief is the idea that linkages between countries provide enhanced opportunities for the international transfer and diffusion of environmentally-beneficial innovations. Our goal in the present paper has been to empirically scrutinise two claims about the conditions under which countries are most likely to realise these gains. The first is that less pollution-efficient countries should improve their pollution-efficiency faster than more pollution-efficient ones, as they incorporate ESTs and environmental policies already adopted in the latter. And second, transnational linkages accelerate the international spread of environmentally-beneficial innovations, and therefore improvements in environment-efficiency. In order to test

[8] This result does not necessarily contradict the literature that casts doubt on whether the Helsinki Protocol had any real effect on emission trajectories, e.g. Murdoch and Sandler (1997) and Ringquist and Kostadinova (2005). None of these studies analyses emissions-efficiency nor are they based on a global sample.

[9] This cannot be directly observed from tables 2 and 3, but follows from the confidence intervals of the estimations.

these claims, we use econometric techniques to examine the dynamics and determinants of CO_2 and SO_2-efficiency, using a panel straddling up to 114 countries over the period 1980-2000.

Regarding the first claim, we find robust evidence of environmental catch-up and convergence. Tests of both β- and σ-convergence confirm the existence of growing similarity in levels of pollution-efficiency over time. Convergence is evident for both our full sample and sub-sample of developing countries. Our results mirror previous findings for CO_2, but derive from a much larger country sample (IEA, 1994; Lindmark, 2004; Mielnik and Goldemberg, 2000). Uniquely, they suggest that catch-up and convergence is not simply restricted to CO_2, but is also apparent for SO_2, a pollutant with very different characteristics.

What might explain these dynamics? One possible explanation is that less pollution-efficient countries are catching-up as they develop (less pollution-intensive) industrial structures similar to those found in more pollution-efficient countries. However, it seems unlikely that the cross-national dynamics of pollution-efficiency are largely a function of structural convergence, with several studies suggesting that structural change has played a comparatively small role in lowering emissions of CO_2 and SO_2 in comparatively polluted countries (e.g. see Kaivo-oja and Luukkanen, 2002; Stern, 2002). Indeed, controlling for shifts in the share of industry value added in our panel data model, we still find robust evidence of convergence in CO_2 and SO_2-efficiency. Instead, a more plausible explanation for our findings is that less pollution-efficient countries are catching-up with more pollution-efficient ones as they adopt ESTs. Again, this interpretation would be consistent with recent decomposition analyses, which find that technological progressions in the direction of lower pollution-intensity have played an important role in reducing CO_2 and SO_2 emissions (de Bruyn, 1997; Kaivo-oja and Luukkanen, 2002; Shrestha and Timilsina, 1997; Wang et al., 2005). It would also tally with evidence pointing to the international spread of ESTs and environmental regulatory policies over time, and moreover, faster rates of diffusion in late adopters (Hilton, 2001; Perkins and Neumayer, 2005).

Proceeding to the second claim, our findings provide broad support for arguments regarding the positive role of transnational linkages. Our estimations point to faster improvements in CO_2 and SO_2-efficiency in countries where a larger share of machinery and manufacturing imports derive from more pollution-efficient economies. However, we find no similar relationship for exports, suggesting that the convergence literature is right to primarily emphasise imports as the leading vehicle for efficiency enhancing technological change (Coe et al., 1997). While our estimation results say nothing about underlying drivers, one possible explanation is international technological and/or regulatory spillovers. Imports of machinery from pollution-efficient countries might be expected to embody high levels of environmental performance, contributing to improvements in domestic environment-efficiency. Similarly, manufactured goods obtained from pollution-efficient countries are more likely to provide the impetus for investments by indigenous firms in more modern, environment-efficient technologies, particularly where they are required in order to remain price and/or quality competitive (Warhurst and Bridge, 1997). It is also possible that import ties with more environment-efficient countries may act as a conduit for the spread of environmentally progressive norms, policy lessons and regulatory instruments, indirectly driving improvements in environment-efficiency (Grubb et al., 2002).

We also find evidence for a role for transnational investment linkages, albeit only in the case of CO_2. We estimate that countries with a larger stock of inward FDI to GDP experience faster improvements in domestic CO_2 emissions-efficiency. This is consistent with previous work by Mielnik and Goldemberg (2002) on the relationship between energy-intensity and FDI in a sample of developing countries. Yet it is also compatible with neoliberal claims about transnational corporations as cross-border carriers of environmentally superior technologies and management practices (UNCTAD, 1999; OECD, 1998). Indeed, a plausible explanation for our finding is that TNCs have access to advanced, energy-efficient technologies, and moreover, deploy these for competitive advantage in host economies. A combination of increased competition and knowledge spillovers mean that indigenous firms follow suit by upgrading the energy-efficiency of their processes and/or product technologies. Our finding that the stock of inward investment does not affect domestic SO_2 emission-efficiency, of course, raises questions about the extent to which FDI positively influences other pollutants. Yet it is worth noting that levels of FDI in the power sector – which typically accounts for the vast bulk of domestic sulphur emissions – were comparatively small during our period of study.

Further reinforcing our paper's findings that transnational linkages between countries positively influence environment-efficiency, we find a role for countries' telecommunications connectivity. The idea that transnational information and communication networks support environmental upgrading is frequently discussed in the case-study literature (Rock, 2002; Mason, 2005; Falkner, 2006). Within these works, telecommunications technologies are portrayed as providing a conduit for the cross-border transfer of coercive pressures, as well as knowledge about environmental technologies, policies and norms. Our study is unique in providing systematic empirical support for the environmental significance of telecommunications linkages and suggests that past large-N research may have overlooked a central channel of environmental convergence.

What are the wider implications of our findings? First, they counter suggestions that environmental progress is restricted to a handful of rich industrialised economies. The fact that environmental laggards are catching-up with environmental leaders suggests that improvements in environment-efficiency are, in fact, geographically widespread. At least for the two pollutants investigated in the present study, more environmentally progressive countries are not racing further and further ahead, leaving behind a pack of struggling, environmental laggards. Instead, it appears that environmentally-beneficial innovations are diffusing across countries, with the result that efficiency improvements made in environmental frontrunner countries are globalising. Second, our findings suggest that advocates of globalisation are right to suggest that transnational linkages between countries can play a positive role, accelerating improvements in domestic environment-efficiency (OECD, 1998). Geographic ties with more environment-efficient countries, in particular, would appear to provide opportunities for ESTs and environmental policies to diffuse.

At the same time, we would caution against over-interpreting these and similar "positive" results. Despite supporting the idea of catch-up, the results presented here do not indicate that countries are converging on an ecologically sustainable path. Our findings simply suggest that countries are becoming more similar in the efficiency with which they use the environment to produce economic output. Indeed, if economic growth increases faster than growth in emissions-efficiency, the net effect on the environment will remain negative. This appears to be the case for CO_2 emissions which, despite ongoing technological change in the direction of greater energy and/or carbon-efficiency, continue to grow rapidly at the global level (IPCC, 2007).

References

Andonova L B, 2003, "Openness and the environment in Central and Eastern Europe: Can trade and investment stimulate better environmental management in enterprises" *Journal of Environment & Development* **12** 177-204

Arellano M, Bond S, 1991, "Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations" *Review of Economic Studies* **56** 277-297

Barro R J, Sala-i-Martin X, 2004 *Economic growth* (MIT Press, Cambridge, MA)

Beck N, Gleditsch K S, Beardsley K, 2006, "Space is more than geography: Using spatial economietrics in the study of political economy" *International Studies Quarterly* **50** 27-44

Chuang Y-C, 2002, "The trade-induced learning effect on growth: Cross-country evidence" *The Journal of Development Studies* **39** 137-154

Coe D T, Helpman E, Hoffmaister A W, 1997, "North-South R&D spillovers" *The Economic Journal* **107** 134-149

Couch G R, 1999, *Non-OECD coal-fired power generation - trends in the 1990s* (IEA Coal Research, London)

Dasgupta S, Mody A, Roy S, Wheeler D, 2001, "Environmental regulation and development: A cross-country empirical analysis" *Oxford Development Studies* **29** 173-187

de Bruyn S M, 1997, "Explaining the environmental Kuznets curve: Structural change and international agreements in reducing sulphur emissions" *Environment & Development Economics* **2** 485-503

Falkner R, 2006, "International sources of environmental policy change in China: The case of genetically modified food" *The Pacific Review* **19** 473–494

Frank D J, Hironaka A, Schofer E, 2000, "The nation-state and the natural environment over the twentieth century" *American Sociological Review* **65** 96-116

Garcia-Johnson R, 2000 *Exporting environmentalism: U.S. multinational chemical corporations in Brazil and Mexico* (MIT Press, London)

Gong G, Keller W, 2003, "Convergence and polarization in global income levels: A review of recent results of international technological diffusion" *Research Policy* **32** 1055-1079

Graham M, 1999 *The morning after Earth Day: Practical environmental politics* (Governance Institute/Brookings Institution Press, Washington, D.C.)

Grossman G M, Krueger A B, 1995, "Economic growth and the environment" *Quarterly Journal of Economics* **110** 353-357

Grubb M J, Hope C, Fouquet R, 2002, "Climatic implications of the Kyoto Protocol: The contribution of international spillover" *Climatic Change* **54** 11-28

Gruber H, 1998, "The diffusion of innovations in protected industries: The textile industry" *Applied Economics* **30** 77-83

Hilton F, 2001, "Later abatement, faster abatement: Evidence and explanations from the global phaseout of leaded gasoline" *Journal of Environment & Development* **10** 246-265

IEA, 1994 *Energy in developing countries - a sectoral analysis* (OECD, Paris)

IEA, 2005 *CO_2 emissions from fuel combustion 1971-2003* (IEA, Paris)

IPCC, 2007, *Climate change 2007 - The physical science basis* (Cambridge University Press for the Intergovernmental Panel on Climate Change, Cambridge)

Islam N, 2003, "What have we learnt from the convergence debate?" *Journal of Economic Surveys* **17** 309-362

ITU, 2003 *World telecommunications indicators database* (International Telecommunications Union, Geneva)

Kaivo-oja J, Luukkanen J, 2002, "Energy and CO_2 dynamics in world regions" *International Journal of Global Energy Issues* **18** 274-293

Lall S, 1992, "Technological capabilities and industrialization" *World Development* **20** 165-186

Lindmark M, 2004, "Patterns of historical CO_2 intensity transitions among high and low-income countries" *Explorations in Economic History* **41** 426-447

Markandya A, Pedroso-Galinato S, Streimikiene D, 2006, "Energy intensity in transition economies: Is there convergence towards the EU average?" *Energy Economics* **28** 121-145

Mason M, 2005 *The new accountability: Environmental responsibility across borders* (Earthscan, London)

Mielnik O, Goldemberg J, 2000, "Converging to a common pattern of energy use in developing and industrialized countries" *Energy Policy* **28** 503-508

Mielnik O, Goldemberg J, 2002, "Foreign direct investment and decoupling between energy and gross domestic product in developing countries" *Energy Policy* **30** 87-89

Murdoch, J C and Sandler T, 1997, "Voluntary cutbacks and pretreaty behavior: The Helsinki Protocol and sulfur emissions" *Public Finance Review* **25** 139-162

Murray W E, 2006 *Geographies of globalization* (Routledge, London)

Neumayer E, Perkins R, 2003, "What explains the uneven take-up of ISO 14001 at the global level? A panel data analysis" *Environment and Planning A* **36** 823-839

Neumayer E, Perkins R, 2005, "Uneven geographies of organizational practice: Explaining the cross-national transfer and diffusion of ISO 9000" *Economic Geography* **81** 237-259

OECD, 1998 *Open markets matter: the benefits of trade and investment liberalisation* (OECD, Paris)

Perkins R, Neumayer E, 2005, "The international diffusion of new technologies: A multitechnology analysis of latecomer advantage and global economic integration" *Annals of the Association of American Geographers* **95** 789-808

Popp D, 2006, "International innovation and diffusion of air pollution control technologies: The effects of NO_X and SO_2 regulation in the US, Japan, and Germany" *Journal of Environmental and Economics and Management* **51** 46-71

Portes, R and Rey H, 2005, "The determinants of cross-border equity flows" *Journal of International Economics* **65** 269-296

Reppelin-Hill V, 1999, "Trade and environment: An empirical analysis of the technology effect in the steel industry" *Journal of Environmental Economics and Management* **38** 283-301

Ringquist E J, Kostadinova T, 2005, "Assessing the effectiveness of international environmental agreements: The case of the 1985 Helsinki Protocol" *American Journal of Political Science* **49** 86-102

Rock M T, 2002 *Pollution control in East Asia: Lessons for newly industrialising economies* (Resources for the Future, Washington, D.C.)

Sandler T, Sargent K, 1995, "Management of transnational commons: Coordination, publicness, and treaty formation" *Land Economics* **71** 145-162

Shrestha R M, Timilsina G R, 1997, "SO_2 emission intensities of the power sector in Asia: Effects of generation-mix and fuel-intensity changes" *Energy Economics* **19** 355-362

Simmons B A, Elkins Z, 2004, "The globalization of liberalization: Policy diffusion in the international political economy" *American Political Science Review* **98** 171-189

Stern, n.d., "Data page", http://www.rpi.edu/%7Esternd/datasite.html

Stern D I, 2002, "Explaining changes in global sulfur emissions: An econometric decomposition approach" *Ecological Economics* **42** 201-220

Taylor M R, Rubin E S, Hounshell D A, 2005, "Control of SO_2 emissions from power plants: A case of induced technological innovation in the US" *Technological Forecasting & Social Change* **72** 697-718

Tews K, Busch P-O, Jörgens H, 2003, "The diffusion of new environmental policy instruments" *European Journal of Political Research* **42** 569-600

UN, 2006 *Commodity Trade Statistics Database (COMTRADE)* (United Nations Statistics Division, New York)

UNCTAD, 2004 *World Investment Directory* (United Nations Conference on Trade and Development, New York and Geneva)

Vogel D, 2000, "Environmental regulation and economic integration" *Journal of International Economics* **3** 265-279

Wang C, Chen J, Zou J, 2005, "Decomposition of energy-related CO_2 emissions in China: 1957-2000" *Energy* **30** 78-83

Warhurst A, Bridge G, 1997, "Economic liberalisation, innovation, and technology transfer: Opportunities for cleaner production in the minerals industry" *Natural Resources Forum* **21** 1-12

WCED, 1987 *Our common future* (Oxford University Press, Oxford)

Weizsäcker E U V, Lovins A B, Lovins L H, 1998 *Factor four: doubling wealth - halving resource use: the new report to the Club of Rome* (Earthscan, London)

Wong W-K, 2004, "How good are trade and telephone call traffic in bridging the gap between income gaps and TFP gaps?" *Journal of International Economics* **64** 441-463

World Bank, 2005 *World Development Indicators on CD-ROM* (IBRD, Washington, D.C.)

Table 1. Unconditional β-convergence analysis.

	(1)	(2)	(3)	(4)
	CO_2 Full sample	CO_2 Developing countries	SO_2 Full sample	SO_2 Developing countries
ln emissions-eff. in 1980	-0.312	-0.270	-0.511	-0.461
	(6.86)***	(5.58)***	(4.48)***	(3.68)***
Constant	0.327	0.239	0.354	0.149
	(4.96)***	(2.98)***	(2.51)**	(1.26)
Countries	112	79	110	76
R-squared	0.25	0.22	0.34	0.31

OLS regression. Dependent variable is period growth in emissions-efficiency from 1980 to 2000.

Absolute robust t-statistics in parentheses.

** significant at 5%; *** significant at 1%

Table 2. The determinants of CO_2-efficiency.

	(1)	(2)	(3)	(4)
	Full sample	Full sample	Developing countries	Developing countries
ln emissions efficiency (t-1)	0.664	0.677	0.642	0.688
	(11.46)***	(12.87)***	(9.31)***	(12.19)***
Machinery and manuf. import weighted spatial lag (t-1)	0.201	0.120	0.220	0.134
	(2.47)**	(1.62)*	(2.64)***	(1.94)*
Machinery and manuf. export weighted spatial lag (t-1)		0.025		0.034
		(0.68)		(0.87)
FDI stock	0.001	0.001	0.003	0.001
	(1.90)*	(1.85)*	(3.13)***	(1.59)
Telecomm. principal comp.	0.011	0.012	0.001	-0.001
	(2.83)***	(3.37)***	(0.07)	(0.16)
ln GDP p.c.	0.291	0.252	0.260	0.195
	(5.48)***	(3.04)***	(3.96)***	(3.22)***
% Industry value added	-0.004	-0.004	-0.002	-0.003
	(2.79)***	(3.04)***	(1.56)	(2.34)*
Observations	1451	1409	959	918
Countries	114	113	85	84
Test of no second-order auto-correlation (p-value in brackets)	0.53	0.64	0.30	0.21
	(0.59)	(0.52)	(0.77)	(0.83)

Arellano and Bond (1991) GMM estimation. Coefficients of year-specific time dummies and constant not reported. Dependent variable is ln emissions-efficiency. Absolute robust z-statistics in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%

Table 3. The determinants of SO_2-efficiency.

	(1)	(2)	(3)	(4)	(5)	(6)
	Full sample	Full sample	Developing countries	Developing countries	Full sample	Full sample
ln emissions efficiency (t-1)	0.617	0.643	0.474	0.633	0.660	0.657
	(5.42)***	(6.44)***	(4.20)***	(6.49)***	(6.05)***	(7.04)***
Machinery and manuf. import	0.396	0.263	0.145	0.090	0.319	0.183
weighted spatial lag (t-1)	(2.87)***	(2.68)***	(1.84)*	(1.20)	(2.46)**	(2.04)**
Machinery and manuf. export		0.041		0.038		0.033
weighted spatial lag (t-1)		(0.97)		(1.19)		(0.76)
FDI stock	0.001	0.001	-0.001	-0.001	-0.001	0.001
	(0.49)	(0.38)	(0.46)	(0.91)	(0.02)	(0.01)
Telecomm. principal comp.	0.049	0.043	0.242	0.142	0.057	0.042
	(2.48)**	(2.52)**	(2.57)**	(2.54)**	(2.38)**	(2.30)**
ln GDP p.c.	0.268	0.285	0.325	0.341	0.230	0.275
	(1.44)	(2.30)**	(2.54)**	(4.13)***	(1.16)	(0.09)
% Industry value added	0.008	0.005	-0.010	-0.007	0.003	0.003
	(0.57)	(0.47)	(3.12)***	(2.75)***	(0.23)	(0.31)
Helsinki Protocol					0.278	0.205
					(2.94)***	(2.90)***
Oslo Protocol					-0.012	-0.003
					(1.02)	(0.27)
ln contiguous emissions					9.93	5.02
					(2.32)**	(1.65)*
Observations	1448	1406	956	915	1448	1406
Countries	113	112	84	83	113	112
Test of no second-order auto-	0.92	0.61	0.77	-0.28	0.80	0.56
correlation (p-value in brackets)	(0.36)	(0.54)	(0.44)	(0.78)	(0.42)	(0.57)

Arellano and Bond (1991) GMM estimation. Coefficients of year-specific time dummies and constant not reported. Dependent variable is ln emissions-efficiency. Absolute robust z-statistics in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%

Appendix 1. Descriptive summary statistics.

CO_2-efficiency:

Variable	Obs	Mean	Std. Dev.	Min	Max
ln emissions efficiency (t-1)	1451	1.00	0.72	-0.99	3.51
Machinery and manuf. import weighted spatial lag (t-1)	1451	0.75	0.16	-0.12	1.20
Machinery and manuf. export weighted spatial lag (t-1)	1418	0.76	0.34	-0.56	2.21
FDI stock	1451	19.22	33.94	0.00	439.76
Telecomm. principal comp.	1451	0.15	1.31	-0.42	10.13
ln GDP p.c.	1451	6.51	1.00	1.73	8.50
% Industry value added	1451	32.27	9.17	7.85	72.69

SO_2-efficiency:

Variable	Obs	Mean	Std. Dev.	Min	Max
ln emissions efficiency (t-1)	1448	-0.26	1.01	-5.54	4.26
Machinery and manuf. import weighted spatial lag (t-1)	1448	0.16	0.41	-0.93	1.30
Machinery and manuf. export weighted spatial lag (t-1)	1415	-0.03	0.47	-1.91	2.26
FDI stock	1448	19.27	33.97	0.00	439.76
Telecomm. principal comp.	1448	0.14	1.30	-0.42	10.13
ln GDP p.c.	1448	6.50	1.00	1.73	8.50
% Industry value added	1448	32.24	9.17	7.85	72.69
Helsinki Protocol	1448	0.30	0.77	0.00	2.77
Oslo Protocol	1448	0.25	0.57	0.00	1.95
ln contiguous emissions	1448	0.17	0.17	-0.02	1.04

Appendix 2. List of countries in sample.

Albania, Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Bahrain, Bangladesh, Belarus, Belgium, Benin, Brazil, Bulgaria, Cameroon, Canada, Chile, China, Colombia, Congo (Rep.), Costa Rica, Côte d'Ivoire, Croatia, Cuba, Cyprus, Czech Republic, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Eritrea, Estonia, Ethiopia, Finland, France, Gabon, Georgia, Germany, Ghana, Greece, Guatemala, Honduras, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Ireland, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Kuwait, Kyrgyz Republic, Latvia, Lebanon, Libya, Lithuania (SO_2 only), Luxembourg, Macedonia, Malaysia, Malta, Mexico, Moldova, Morocco, Mozambique, Myanmar, Namibia, Nepal, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Russian Federation (CO_2 only), Saudi Arabia, Senegal, Singapore, Slovak Republic, Slovenia, South Africa, South Korea (CO_2 only), Spain, Sri Lanka, Sudan, Sweden, Syria, Tajikistan, Tanzania, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, Turkmenistan, Ukraine, United Arab Emirates, United Kingdom, United States, Uruguay, Venezuela, Vietnam, Yemen, Yugoslavia (CO_2 only), Zambia, Zimbabwe.