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How do domestic attributes affect international spillovers of CO_2-efficiency?

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Abstract

Although there is evidence that CO_2-efficiency enhancing innovations in one country diffuse into other countries to contribute to the goals of climate change mitigation, very little is known about the conditions under which such international spillovers are most likely to take place. Our contribution in the present article seeks to address this gap by examining whether the strength of cross-border CO_2-efficiency interdependence working through import ties and inward foreign direct investment (FDI) stocks is greater in (a) countries with lower existing levels of domestic CO_2-efficiency and (b) countries with greater social capabilities in terms of a better educated workforce and a less risky institutional environment for investment. We find that less CO_2-efficient countries and countries with a more investment-friendly institutional environment experience stronger FDI-weighted CO_2-efficiency spillovers, whereas a higher level of human capital increases domestic receptivity to import-weighted international spillovers.

spillover, efficiency, imports, foreign direct investment, education, institutions

1. Introduction

Within debates surrounding the dynamics of anthropogenic emissions, growing attention has been paid to the existence of international spillovers (Bosetti et al. 2009; Golombek and Hoel 2005; IPCC 2007). These are hypothesised to occur when greenhouse gas (GHG) efficiency-enhancing technologies and performances in one economy diffuse ("spillover") into another economy (Grubb et al. 2002; Sijm et al. 2004; Stern 2007). Recent work has lent support to the existence of international spillovers, finding that a higher level of import-weighted carbon dioxide (CO_2)-efficiency in other countries is positively correlated with domestic CO_2-efficiency, indicative of the existence of cross-national spatial interdependencies in emissions (Perkins and Neumayer 2008, 2009).

Missing from this work, however, has been any attempt to investigate the influence of domestic attributes over international spillovers of CO_2-efficiency. Instead, attention has focused solely on variations in average levels of connectivity-weighted CO_2-efficiency in other countries, on the assumption that domestic attributes do not exert a conditioning influence. Yet there are compelling reasons to suspect that characteristics of the focal country might well influence the degree of cross-national spatial interdependence.

Our goal in the present article is to explore this hitherto neglected issue. Specifically, we examine whether the strength of spatial interdependence working through import ties and inward foreign direct investment (FDI) stocks is greater in (a) countries with lower existing levels of domestic CO_2-efficiency and (b) countries with greater social capabilities, defined here in terms of human capital and the institutional environment for investment. Similar attributes have been invoked in related conceptual and empirical research which has investigated income catch-up, convergence and economic productivity spillovers (Abramovitz 1986; Coe et al. 2008; Fagerberg 1994; Keefer and Knack 1997). They have also been discussed in work which has considered the conditions under which technology transfer and spillovers are most likely to contribute to the goals of climate mitigation (Ang 2009; De Cian 2007; IPCC, 2000, 2007). However, we are unaware of any work which has examined empirically the influence of existing emissions-efficiency or social capabilities in mediating the strength of international spillovers in the case of CO_2-efficiency, or indeed similar measures of environmental performance.

Consistent with theoretical predications, our work shows that domestic factors mediate cross-national spillovers, although the influence of individual attributes varies between import and FDI channels. Hence, we find that less CO_2-efficient countries and countries with a more business-friendly institutional environment experience stronger inward FDI-weighted spillovers, whereas a better educated workforce increases domestic receptivity to import-weighted international spillovers. Thus, while different attributes matter, country characteristics would appear to systematically shape the degree to which higher levels of CO_2-efficiency abroad spillover domestically.

2. International spillovers

The basic idea underlying international spillovers is that innovations, behaviours and performances in one country spillover across national borders by altering the optimal choices for actors in other countries (Pitlik 2007). Within the literature on climate mitigation, particular significance has been ascribed to technology spillovers, whereby efficiency-enhancing technological efforts diffuse cross-nationally, whether in embodied (i.e. physical plant and equipment) or disembodied (i.e. know-how, know-why, etc.) form (IPCC 2007; Nagashima and Dellink 2008). Their assumed importance is two-fold. First, technology plays a central role in improving domestic CO_2-efficiency, and can therefore potentially counteract the emissions-enhancing effects of scale (Peters et al. 2007; Worrell et al. 2009). Second, a large share of the world's innovative efforts, including research and development (R&D) instrumental in improving CO_2-efficiency, takes place in a handful of developed economies (OECD 2008). International technology spillovers allow other countries – including developing ones – to take advantage of these innovative efforts and, moreover, potentially below the inventor's original costs (Rao et al. 2006; Stern 2007).

An important corollary of international spillovers is that efficiency-enhancing technological change in one country may diffuse across national borders to raise domestic CO_2-efficiency in other countries. On the supply-side, such spillovers may arise from the deliberate transfer of embodied or disembodied technology, e.g. via the purchase of equipment from foreign vendors, licensing agreements, internal transfers of new technology from a transnational corporation's (TNC's) parent to its overseas subsidiary. Additionally, technology transfer may take place indirectly as a by-product of these market transactions, in the form of knowledge spillovers (Saggi 2002). These positive externalities arise from the quasi public good characteristics of technological knowledge and mean that firms can appropriate the benefits of foreign technological innovation without fully compensating the original inventor (Popp 2006).

On the demand-side, CO_2-efficiency enhancing spillovers may be the product of competitive pressures, transmitted via cross-border price and/or quality effects (De Cian 2007; Grubb et al. 2002). As an example, the uptake of more advanced, energy-efficient capital equipment (which is also more CO_2-efficient) may help firms based in one country to reduce their production costs, creating price-based pressures for foreign firms which compete in the same product markets to adopt similar efficiency-enhancing technologies (Luken and Van Rompaey 2008; Perkins 2007). Another aspect of demand-side spillovers stems from spatial interdependence in policy choices. Whether for competitive, reputational or technical reasons, public or private policies adopted by actors in one territory may be "copied" by counterparts in other territories (Busch et al. 2005). Again, this may indirectly create demand for technologies which enhance domestic CO_2-efficiency, as in the case of promotional policies supporting the uptake of new renewables in electricity generation (OECD 2008).[1]

Regardless of the specific mechanism, international spillovers logically depend on transnational linkages connecting geographically dispersed countries, which serve as conduits for embodied and disembodied knowledge, policy innovations, and competitive pressures. Most widely discussed in the context of international climate spillovers are cross-border economic ties created respectively by trade and FDI (De Cian 2007; Mielnik and Goldemberg 2002; Perkins and Neumayer

[1] As hypothesised in the literature, policy-driven price effects (e.g. from carbon taxes) in higher-regulating countries may give rise to "negative" international spillovers, as carbon-intensive industrial production shifts to lower-regulating countries (Sijm et al., 2004). We do not rule out the possibility of so-called "carbon leakage". Yet it is not the central focus of our study which is concerned with relative (i.e. CO_2-efficiency) rather than absolute measures (i.e. aggregate CO_2) of GHG emissions and, in any case, we partly control for dynamic shifts in economic structure in our research design.

2008; Peterson 2008). Picking-up on this work, we focus on international spillovers in CO_2-efficiency through these two linkages in the present study, and specifically on imports of machinery and manufactured goods and inward FDI stock.

3. The moderating effects of the domestic context

One way in which scholars have sought to examine the existence of international spillovers is through the use of spatial lags (Prakash and Potoski 2007). Also known as spatial autoregressive models, spatial lags allow quantitative researchers to investigate whether the connectivity-weighted value of an environmental attribute in other countries is correlated with the same domestic attribute in a focal economy, and therefore the extent to which innovations, behaviours and performances diffuse across borders via transnational linkages. Using this spatial econometric approach, Perkins and Neumayer (2008, 2009) find evidence for spillovers. They show that higher levels of machinery and manufactured goods import-weighted CO_2-efficiency in other economies is associated with higher levels of domestic CO_2-efficiency. Yet the authors fail to find evidence that inward FDI stock-weighted foreign CO_2-efficiency influences domestic efficiency.

The present article builds on this work, but takes the analysis one crucial step further. In particular, we analyse whether domestic attributes influence the degree of connectivity-weighted spatial CO_2-efficiency interdependence. That is, we examine whether characteristics of the focal country amplify or attenuate the influence of other countries' CO_2-efficiency on domestic efficiency, where other countries are defined as

(i) exporters of machinery and manufactured goods to the focal country and (ii) sources of inward FDI to the focal economy.

Theoretical inspiration for our decision to investigate the influence of domestic attributes primarily comes from related work concerned with economic productivity spillovers, income convergence and catch-up. This stream of scholarship has invoked two sets of factors which might plausibly influence the strength of spatial interdependence: (a) relative backwardness, in the sense of countries' comparative inefficiency; and (b) social capabilities, in terms of countries' capacity to acquire and absorb new technology (Abramovitz 1986; Fagerberg 1994). Drawing from this work, we hypothesise that similar factors could well influence the degree to which higher levels of CO_2-efficiency in other countries to which a particular economy is linked via transnational economic ties spillover to raise domestic CO_2-efficiency.

3.1 Relative backwardness (the "inefficiency" thesis)

The idea that relative inefficiency or backwardness[2] might be an advantage in appropriating new, more efficient technology has its roots in the work of Gerschenkron (1962) who explored the conditions under which latecomer economies develop. Similar ideas underpin the so-called catch-up thesis – also known as the convergence hypothesis – which maintains that domestic rates of economic productivity growth are positively related to the relative backwardness of economies (Abramovitz 1986). According to technology transfer variants of these theories, catch-up takes place because less efficient economies have a larger global stock of un-

[2] We do not seek to use the term backwardness in a pejorative sense, but, rather, to maintain consistency with relevant theoretical literature.

tapped knowledge from which to draw, meaning that they can make more rapid leaps in productivity (Findlay 1978). Moreover, such countries can take advantage of learning economies and knowledge externalities arising from technological efforts in frontrunner economies, which reduce the costs of new technologies, improve their performance and increase adoption returns (Grubb 2004; Perkins and Neumayer 2005; Rao et al. 2006).

The same logic can be extended to CO_2-efficiency. Less efficient countries are more likely to make significant gains in domestic carbon-efficiency by incorporating previously unexploited or under-exploited CO_2-efficient technologies innovated in high-efficiency economies (Ang 2009). Moreover, the economic savings from rapidly adopting these technologies should be greater for less environment-efficient economies, in that imitation is less costly than innovation. Competitive price and/or quality effects emanating from producers in high-efficiency economies mean that competitors in CO_2-inefficient countries – whose implied technological backwardness might well render them uncompetitive – should also face strong economic incentives to catch-up technologically with more pollution-efficient countries[3] (Grubb et al. 2002).

Accepting these arguments, it follows that transnational economic linkages with more CO_2-efficient countries should spillover more strongly into higher levels of domestic efficiency in focal countries with lower levels of existing CO_2-efficiency.

3.2 Social capabilities (the "capabilities" thesis)

[3] Note, there may be circumstances where competition-driven technological upgrading reduces CO_2-efficiency, although we believe that such instances will be outweighed by those which increase efficiency.

Although intuitively appealing, the thesis that less efficient countries should benefit more in terms of productivity growth from the global stock of technological knowledge has been criticised by scholars who argue that it does not tell the full story. In particular, as well as domestic levels of inefficiency, productivity gains depend on “social capabilities” (Ohkawa and Rosovsky 1973), generally understood as the suite of capacities required to adopt and absorb foreign technology in ways which are appropriate to local needs (Bell and Pavitt 1993).

Two main categories of social capability have been invoked in the economics literature. The first is human capital. Countries with educated workforces are assumed to be better-placed to effectively utilize currently-available foreign technology to improve domestic productivity. Hence, not only should they find it cheaper and easier to adopt, optimise and improve physical equipment acquired from abroad, but also exploit productivity enhancing knowledge externalities embedded in transferred technology (Facundo et al. 2009; Lall 1992). Human capital, in turn, better-allows domestic firms to respond to competitive pressures from more productive foreign competitors by upgrading their technologies.

Another oft-discussed aspect of social capability is the institutional environment. Within this broad category, a wide range of domestic attributes have been mentioned, including corruption, rule of law, security of property rights, and the ease of doing business (Coe et al. 2008; Keefer and Knack 1997). Yet a common feature of arguments which emphasise institutional aspects is the assumption that the institutional environment affects business risk. In doing so, it influences the propensity of foreign business actors to transfer new technologies, and the willingness of potential recipients to make domestic investments required to acquire new technological hardware and absorb associated knowledge.

An important corollary is that countries without appropriate capabilities will fail to fully capture (potential) productivity gains derived from technological efforts made in more productive countries. In fact, similar points have been made in work concerned with the conditions for the successful transfer of GHG-efficient technologies, which has highlighted the importance of a suitable “enabling environment” (IPCC 2000; Rock et al. 2009; UNDP 2007; UNFCCC n.d.). Amongst the attributes mentioned in this regard is the existence of domestic technological capabilities (skills, etc.) required to acquire, absorb and innovate new climate mitigation technologies, as well as domestic institutions which mitigate commercial risks for investors and technology transfer agents. We therefore hypothesize that transnational economic ties with more CO_2-efficient economies should spillover more strongly into higher levels of domestic CO_2-efficiency in countries (a) with a better educated workforce and (b) where the institutional environment for business investment is less risky.

4. Previous evidence

We are aware of no existing quantitative research which has examined the influence of the above mediating domestic attributes – i.e. domestic efficiency and social capabilities – on intCO_2-efficiency spillovers. Yet evidence from a wider set of environmental and non-environmental studies provides a degree of support for both the inefficiency and capabilities thesis.

Several studies lend weight to the idea that less efficient countries gain more (i.e. in terms of higher domestic efficiency) from international spillovers than their more efficient counterparts. Hence there is some evidence that foreign knowledge spillovers have a greater positive impact on domestic economic productivity growth where countries are currently relatively less productive (Castellani and Zanfei 2003; Griffith et al. 2004; Peri and Urban 2006; Sjöholm 1999; Xu and Wang 2000). However, other studies contradict these results, finding that less productive firms (Kokko, Tansini et al. 1996; Girma, Greenaway et al. 2001; Dimelis 2005) and/or poorer countries (Crespo, Martín et al. 2004) benefit less from international technology spillovers. Still others find a U-shaped relationship between foreign productivity spillovers, on the one hand, and relative efficiency and wealth, on the other (Meyer and Sinani 2009).

Turning to work which has examined environment-efficiency, Perkins and Neumayer (2008) find cross-national convergence at the global level in CO_2-efficiency, albeit only at moderate rates. These findings are, in principle, consistent with the story of less efficient countries improving their domestic CO_2-efficiency more rapidly by incorporating previously unexploited or under-exploited technologies from abroad.

Another stream of work presents evidence that, directly or indirectly, supports the importance of social capabilities. Multiple studies have shown that rates of productivity growth and/or catch-up associated with international technology spillovers are positively correlated with levels of human capital (Coe et al. 2008; Crespo et al. 2004; Engelbrecht 1997; Falvey et al. 2007; Frantzen 2000; Wang 2007; Xu and Chiang 2005). These findings mirror research which demonstrates that more modern, advanced technologies diffuse faster in better-educated countries (Kiiski and Pohjola 2002; Perkins and Neumayer 2005).

Studies have also found that rates of economic growth (Mauro 1995), productivity growth (Coe et al. 2008), and income convergence (Keefer and Knack 1997) derived from international technology spillovers are influenced by the domestic institutional environment. Although the nature and scope of relevant institutional aspects have been interpreted differently by different authors, amongst the variables identified in the literature as statistically significant correlates have been the "ease of doing business"," "rule of law", "contract enforceability" and "executive constraints" (Coe et al. 2008; Keefer and Knack 1997).

5. Research design

5.1 Dependent variable

The dependent variable for our estimations is the log of a country's CO_2-efficiency, i.e. GDP divided by CO_2 emissions. GDP at exchange rates is known to underestimate effective purchasing power in lower income countries and we therefore use GDP on a purchasing power parity (PPP) basis. Data for both CO_2 emissions and GDP are taken from IEA (2008). The unit of analysis is the country year. Our global sample comprises 77 (developed and developing) countries over the period 1984-2005, with coverage being limited only by the availability of data. The list of countries included in the study is shown in the appendix.

5.2 Explanatory variables

We focus on international spillovers through two types of transnational economic linkage. The first is created by imports of machinery and manufactured goods. Imports of machinery (e.g. steel plant) and manufactures (e.g. automobiles) from CO_2-efficient economies should plausibly embody higher levels of energy/carbon-efficiency than from CO_2-inefficient ones. The adoption of this technology in the importing economy might therefore be expected to raise domestic CO_2-efficiency (Perkins 2007; Rock et al. 2009). More advanced technical knowledge embedded in CO_2-efficient technology also increases the possibilities for knowledge spillovers which raise CO_2-efficiency, as domestic firms learn from imported technology, diffusing the efficiency-enhancing benefits of imports beyond the transferred physical artefacts (De Cian 2007). Another way in which imports of machinery and manufactured goods from more CO_2-efficient economies might diffuse superior levels of CO_2-efficiency is through competitive effects. Especially for energy-intensive production and consumption technologies, where levels of energy consumption may be a factor in consumer choice, imports of superior, efficient technology may stimulate domestic firms to improve the energy-efficiency of their own process or product technologies.

Another reason to focus on imports of machinery and manufactured goods in CO_2-efficiency enhancing technology spillovers is that their influence has been demonstrated in previous work. Most relevant is Perkins and Neumayer (2008, 2009) who find that levels of CO_2-efficiency in other countries weighted by machinery and manufactured goods imports are positively correlated with domestic levels of CO_2-efficiency. However, similar findings have been made by scholars who have investigated productivity spillovers, with imports of capital goods from more productive economies giving rise to higher levels of domestic productivity (Coe and

Helpman 1995; Eaton and Kortum 1996; Falvey et al. 2004). In order to construct our import-weighted spatial lag variable, we use for the weighting matrix data on machinery and manufactured goods imports of country *i* from countries *k*, with data from UN (2009).

A second linkage examined in the present study is inward FDI although, unlike our import linkage variable, lack of disaggregated investment data with widespread geographic coverage means that we are unable to restrict our analysis to sectors most likely to impact domestic CO_2-efficiency. Again, there are compelling reasons to expect FDI from more CO_2-efficient countries to play a leading role in diffusing superior levels of CO_2-efficiency. Most importantly, TNCs innovate, own, operate and vend many of the world's advanced technologies, including ones with superior CO_2-efficiency (UNCTAD 2007). Indeed, these ownership-based advantages allow transnationals to compete with domestic rivals, who have advantages of their own. Through their investments in host economies, TNCs from more CO_2-efficient economies may transfer advanced, environment-efficient technologies and organizational practices directly, incorporating them in process equipment, or engineering them into their products (Fisher-Vanden et al. 2004; Mielnik and Goldemberg 2002; OECD 1997; Prakash and Potoski 2007).

Indirectly, the presence of TNCs is known to give rise to knowledge spillovers, as domestic firms learn from knowledge embedded in the technologies and practices operated by their foreign rivals, e.g. by observing, reverse engineering, labour turnover, etc (Cole et al. 2008; Facundo et al. 2009). The involvement of TNCs from more CO_2-efficient countries may additionally give rise to increased price and/or quality competition which incentivise firms to invest in more modern, efficient technologies and, moreover, raise average levels of efficiency by forcing inefficient firms out of business (Ang 2009; Saggi 2002).

Empirical support for the influence of FDI is more mixed. For a sample of 20 developing countries, Mielnik and Goldemberg (2002) find that inward FDI is negatively correlated with energy-intensity, albeit using a rudimentary bivariate correlation without controls. Using a larger sample of developed and developing countries, and a multivariate estimation model, Perkins and Neumayer (2008) find that higher levels of aggregate inward FDI stock is associated with higher domestic CO_2-efficiency. Yet, deploying a more sophisticated spatial lag specification, Perkins and Neumayer (2009) demonstrate that levels of inward FDI stock-weighted CO_2-efficiency in other countries have no statistically significant influence on domestic CO_2-efficiency in developing countries. Hübler and Keller (2008) also fail to find any consistent evidence that FDI flows into developing countries reduce domestic energy-intensity. Similarly ambiguous results for FDI can be found in the productivity spillovers literature (Hejazi and Safarian 1999; Lai et al. 2006; Pottelsberghe de la Potterie and Lichtenberg 2001). Our FDI-weighted spatial lag measure is constructed using UNCTAD (2008) data on the stock of inward foreign direct investment in country *i* originating from countries *k* as the connectivity variable.

We also include variables which seek to capture the existing level of domestic efficiency and social capabilities. In our first regression model, we include these as separate explanatory variables, with a view to analysing whether they have an independent influence on domestic CO_2-efficiency. Yet our principal concern is whether domestic attributes have a "conditioning" influence on the degree of international spillovers. In our main estimations, we therefore use an interactive model specification, whereby variables measuring existing levels of efficiency and aspects of social capabilities are interacted with the import- and inward FDI-weighted spatial lags.

Levels of domestic efficiency are measured by the log of a country's CO_2-efficiency lagged by one period, i.e. by the temporally lagged dependent variable.[4] As per models of cross-national catch-up, we expect less CO_2-efficient countries to improve their domestic CO_2-efficiency faster, and for the import- and inward FDI-weighted CO_2-efficiency spillovers to be stronger in these countries.

In order to measure social capability, we use two variables, each intended to capture a key enabling attribute identified in the literature. The first is human capital. As an attribute in its own right, we expect countries with educated workforces to have higher domestic CO_2-efficiency, since they should be better-placed to innovate, adopt and improve more CO_2-efficient technologies. Similarly, human capital is likely to have an important conditioning influence on international spillovers, with educated workforces possessing greater abilities to effectively utilise and optimise transferred equipment to suit local conditions, assimilate foreign technological knowledge derived from imports and FDI, as well as respond to associated competitive pressures which stimulate efficiency-enhancing technological catch-up. In order to capture human capital, we use data from Cohen and Soto (2007) on the secondary school completion ratio of the population aged 25 and above, a measure which has been widely-used in past studies (e.g. Wang 2007).

Another category of social capability explored in the present study is the institutional environment for investment. From a theoretical perspective, by influencing the degree of business risk, the institutional environment should affect the

[4] Note that while this variable seemingly measures backwardness rather than relative backwardness, we also include year-specific fixed effects, which means that for each country the emissions-efficiency variable measures deviations from the period-average of emissions-effiency and, thus, in effect measures relative backwardness.

extent to which firms might be willing to invest in capital-intensive, carbon-efficient plant and equipment. Additionally, the institutional environment might be expected to shape firms' willingness to make learning investments, and thus their ability to more fully appropriate foreign knowledge spillovers.

Two criteria were used to select our measure of the institutional environment, namely: (i) that it should capture institutional attributes which directly influence firms' decisions to make efficiency-enhancing investments and, moreover, in ways that affect the degree of spillover from the spatial lag variables; and (ii) the constituent measure should exhibit variability within countries over time so as to reduce the possibility of collinearity with the country fixed effects used in our study. Accordingly, we decided against using a number of institutional measures such as bureaucratic quality or rule of law, whose influence over firms' investment decisions is only indirect and which have little temporal variability. Instead, we make use of a measure which fulfils both of the above criteria, called "investment profile" (PRS 2009). Published in the *International Country Risk Guide*, investment profile is a composite of three factors: contract viability/expropriation, profits repatriation and payment delays. The measure runs from 0-12, with 0 representing the highest amount of risk, and 12 the lowest, i.e. the most investor-friendly level.

Admittedly, this variable is more likely to be relevant for our FDI-weighted spatial lag, relating directly to the risks faced by foreign investors. Unfortunately, we are unaware of any similar measure which captures the equivalent business risk faced by domestic investors, and especially firms who might acquire plant and equipment from abroad or otherwise exploit knowledge embedded in imports. From a conceptual perspective, however, we believe that the investment profile variable might well also capture risk which affects spillovers from imports of machinery and manufactured goods. Hence, an institutional environment which poses greater business risk to foreign investors is also one which is likely to reduce the willingness of domestic actors to purchase capital-intensive technologies from abroad, as well as to make the sorts of investments required to make productive use of imported foreign technologies and associated knowledge.

5.3 Control variables

We include the share of industry in value added to control for the fact that more industry-intensive economies should, all other things equal, be more CO_2-intensive. Industry directly and indirectly accounts for approximately 37% of GHG emissions (Worrell et al. 2009), suggesting that a failure to take account of cross-country differences in industry-intensity might well bias the estimates.

We also include GDP per capita to control for income-dependent demand- and supply-side effects which might plausibly influence domestic CO_2-efficiency. Regarding the former, countries with wealthier populations have tended to demonstrate greater concern for climate change, creating political and market demand for measures to reduce CO_2 emissions. At a multilateral level, richer countries have also faced greater normative obligations to address domestic emissions, institutionalised into binding emission reduction commitments for Annex I (i.e. developed) countries under the Kyoto Protocol. Although the compliance period (2008-2012) for these commitments is beyond the end of our study period, signatory governments have nevertheless been active in initiating actions to address domestic GHG emissions long before this time. On the supply-side, richer countries should command greater financial capabilities required to innovate, commercialise and implement CO_2-efficient technologies, which are often more capital-intensive (IPCC 2007; Worrell et al. 2009). Table 1 provides summary descriptive statistical information for all variables included in the study.

5.4 Model and estimator

We estimate variants of the following model (*i* stands for country, *t* for time):

$$
\begin{aligned}
(1)\ \ln y_{it} = {} & \alpha_i + \beta_1 \ln y_{it-1} + \beta_2 \ln GDPpc_{it} + \beta_3 \%indust_{it} + \beta_4 edu_{it} + \beta_5 invprof_{it} \\
& + \beta_6 \sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} + \beta_7 \sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \\
& + \beta_8 \sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1} + \beta_9 \sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1} \\
& + \beta_{10} \sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it} + \beta_{11} \sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it} \\
& + \beta_{12} \sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot invprof_{it} + \beta_{13} \sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot invprof_{it} \\
& + \delta_t + u_{it}
\end{aligned}
$$

where y_{it} is the dependent variable, α_i represent country-specific fixed effects, $\ln y_{it-1}$ is the temporally lagged dependent variable, $GDPpc_{it}$ is a country's per capita income, $\%indust_{it}$ its industrial share of GDP, edu_{it} is the level of a country's human capital, $invprof_{it}$ is a country's investment profile, $\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1}$ and $\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1}$ represent the two spatial lag variables described in more detail below, δ_t represent year-specific fixed effects and u_{it} is the error term. We find evidence for the "inefficiency" hypothesis if β_8 and/or β_9 are statistically significantly negative since then the degree of spillover stemming from the spatial lag variables $\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1}$ and $\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1}$, respectively, becomes smaller the higher the country's existing efficiency, or greater the lower a country's existing CO_2-efficiency. We find evidence for the "capabilities" hypothesis if β_{10} and/or β_{11} and β_{12} and/or β_{13} are statistically significantly positive since then the degree of spillover from the spatial lag variables becomes stronger the higher the domestic level of human capital and the less risky the institutional environment for investment.

The country-specific fixed effects account for unobserved country differences influencing domestic pollution-efficiency which do not vary, or vary very little over time, and which might be correlated with our explanatory variables. The year-specific fixed effects capture time-specific global trends influencing emissions efficiency. Country- and time-specific fixed effects are also necessary to prevent spurious regression results for the spatial lag variables as they account for unobserved spatial heterogeneity and common shocks and common trends (Plümper and Neumayer 2009).

We estimate equation (1) with Arellano and Bond's (1991) dynamic generalized method of moments (GMM) instrumental variables estimator with robust standard errors. This estimator is necessary because of the simultaneous inclusion of the temporally lagged dependent variable and country-specific fixed effects, which would cause Nickell (1981) bias in a simple fixed effects estimation. Arellano and Bond's estimator has the additional 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. The estimator works by first-differencing equation (1), which eliminates the country-specific fixed effects, and by using past levels of the lagged dependent variable and the endogenous variables lagged by two or more periods as respective 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 can be tested and the test results fail to reject this assumption. Our T is relatively large, which gives a very large number of potential instruments. Using too many instruments can bias the estimation results (Roodman 2007). We have therefore restricted the use of lagged instruments to a maximum total of six.

6. Results

Table 2 presents the estimation results. We start off with our estimations where the spatial lag and explanatory variables are entered on their own, i.e. without any interaction effects (column 1). As anticipated, we find evidence for conditional convergence in that the coefficient of the temporally lagged dependent variable minus one is statistically significantly negative throughout,[5] suggesting that countries with lower existing domestic levels of efficiency improve their CO_2-efficiency faster. This finding is consistent with the catch-up story and, moreover, with Perkins and Neumayer (2008) who find evidence for moderate rates of cross-national convergence in levels of CO_2-efficiency over time. Conversely, we find that our education measure has no statistically significant influence by itself, and the investment profile measure has an unexpected negative impact on domestic CO_2-efficiency. Regarding the control variables, as anticipated we find that richer countries have higher domestic CO_2-

[5] This cannot be directly observed from tables 1 and 2, but follows from the confidence intervals of the estimated coefficients.

efficiency, whereas countries with a higher share of industry in value added have lower efficiency.

Moving to our non-interacted spatial lag variables, we find that higher machinery and manufactured goods import-weighted CO_2-efficiency in other countries is positively and statistically significantly correlated with higher domestic CO_2-efficiency, a result which mirrors the one reported in Perkins and Neumayer (2008, 2009). However, we find no similar relationship for FDI, with the estimated coefficient of the inward investment-weighted spatial lag variable statistically indistinguishable from zero. Again, this result is similar to the findings of Perkins and Neumayer (2009), although their sample is restricted to developing countries only. The estimated degree of international spillover through imports is moderately strong. A one percent increase in import-weighted foreign CO_2-efficiency is associated with approximately 0.3% rise in domestic CO_2-efficiency in the short-run and an approximately 0.68% rise in the long-run.

Could it be that the insignificant result for the spatial lag variable weighted by inward FDI stock arises because there are important conditioning effects not captured by the model specification in column 1? In column 2, we interact the spatial lag variables with domestic efficiency lagged by one period. The respective coefficients for the interaction effect variables with the import and inward FDI stock spatial lags are both negative as expected, but only statistically significant for the spatial lag weighted by inward FDI stocks. This suggests that the degree of FDI-weighted spatial interdependence for CO_2-efficiency is greater for countries whose own CO_2-efficiency is lower. This result is consistent with theoretically-derived predications from models of relative backwardness, catch-up and convergence.

In column 3, we add interactions of the spatial lag variables with our educational and institutional investment environment variables. We find that the level of human capital has a positive and statistically significant impact on the degree of import-weighted spatial interdependence. That is, our estimations suggest that higher foreign levels of CO_2-efficiency in a country's major import partners spillover more strongly into improved domestic CO_2-efficieny where a larger share of the workforce in the importing country is educated, echoing similar results from statistical work into generic productivity spillovers (Crespo et al. 2004; Frantzen 2000). Yet no similar statistically significant conditioning effect of education is found for the FDI stock-weighted spatial lag variable.

We also find some evidence that the institutional environment governing business risk has a conditioning influence on the strength of CO_2-efficiency enhancing international spillovers. The coefficient for the inward FDI-weighted spatial lag interacted with our investment profile measure is positive and statistically significant. The equivalent coefficient for the import-weighted spatial lag, however, fails to achieve statistical significance. In short, while a less risky investment environment would appear to increase the degree to which countries benefit from CO_2-efficiency enhancing spillovers from the source countries of their major foreign investors, the same attribute does not increase the strength of international spillover via import-weighted linkages with more CO_2-efficient countries.

Note, with interacted variables, the coefficients of the constituent terms on their own no longer have the same meaning as in non-interacted models, and all that really matters therefore are the coefficients of the interacted variables. The insignificant coefficients in column 3 of the spatial lag variables, which constitute one part of two interaction terms each, do not imply the absence of spillovers as such.

Rather, they would only indicate the absence of spatial dependence for observations in which the temporally lagged dependent variable, the educational variable and the investment profile variable are negative, zero or have very low values, i.e. in countries whose existing level of CO_2-efficiency is very low and which have very little existing levels of education and which pose a high risk for foreign investors. Similarly, the negative coefficient of the educational variable does not mean that education has a negative effect on efficiency in general, only that it would have a negative effect for those observations for which the imports-weighted spatial lag variable is negative, zero or has very low values, i.e. in countries whose major trade partners are very CO_2-inefficient.

7. Conclusions and discussion

Although there is growing evidence that CO_2-efficiency enhancing innovations in one country diffuse into other countries to contribute to the goals of climate mitigation, very little is known about the domestic conditions under which such international spillovers are most likely to take place (IPCC 2007; Peterson 2008). Our contribution in the present article seeks to address this gap. Focusing on two central channels of spillover, imports of machinery and manufactured goods and inward FDI, we examine how three domestic attributes – existing domestic CO_2-efficiency, human capital and the institutional environment for investment – influence international CO_2-efficiency spillovers.

Our statistical findings, based on a sample of 77 countries over the period 1980-2005, are revealing. We show that countries with lower domestic CO_2-

efficiency not only improve their efficiency faster, but that they also experience stronger international spillovers from more CO_2-efficient foreign countries which are major direct investors in the host economy. These results mirror previous work which has similarly found evidence for cross-national convergence in CO_2-efficiency (Perkins & Neumayer, 2008).

The results reported here also advance on previous work. First, our estimations provide evidence that human capital positively influences the degree of international CO_2-efficiency spillovers from foreign countries, albeit only from major exporters of machinery and manufactured goods into the domestic economy. Second, Perkins & Neumayer (2009) found that levels of FDI-weighted CO_2-efficiency in other economies had no statistically significant influence on domestic CO_2-efficiency. The findings here suggest that this previous result may be a consequence of failing to take into account important domestic conditioning factors, namely, the fact that such spillovers are much stronger in less CO_2-efficient countries and in countries with a less risky institutional environmental for investment.

Although indicating that domestic attributes influence the strength of international spillovers in systematic and predictable ways, it is instructive that the conditioning impact of individual attributes varies between import and FDI channels. At face value, these differences are perhaps surprising, in that there are theoretical arguments to support the influence of all three attributes across both sets of transnational linkage. Yet there are a number of possible explanations for these discrepancies. That existing domestic CO_2-efficiency matters for the degree of spillover from inward FDI, but not imports, might be explained by the observation that TNCs frequently transfer modern, efficient proprietary technologies and associated environmental management practices as part of their investments in host economies (OECD 1997; Perkins 2007; UNCTAD 2007; Warhurst and Bridge 1997). Inward FDI should therefore logically be accompanied by a greater efficiency-enhancing effect in less CO_2-efficient countries where the gap between currently deployed technologies and technologies transferred by TNCs is likely to be larger. Although imports might also serve as a vehicle for the cross-border transfer of the latest, carbon-efficient technologies, the actual embodied CO_2-efficiency in imports is likely to depend more on the demand profile from domestic actors, and there is no guarantee that actors in less efficient countries will demonstrate a preference for more CO_2-efficient technologies (Luken and Van Rompaey 2008; Perkins 2007; Worrell et al. 2009).

Anomalies in the case of domestic CO_2 efficiency might also be (partly) explained by another discrepancy, namely, that education exerts a conditioning influence in the case of import-weighted connectivity, but not FDI-weighted connectivity. FDI is likely to be accompanied by the internal transfer of knowledge, skills and capabilities required to make productive use of new technology (Epstein and Roy 1998; Rock et al. 2009). The ability of countries to take full advantage of imported technologies, on the other hand, is likely to depend on the wider existence of an educated workforce. Indeed, it could be that less CO_2-efficient countries have less educated adult populations, which might account for the result that such economies do not appear better-placed to exploit efficiency gains derived from imported machinery and manufactured goods.

The difference in our results for imports and inward FDI regarding the conditioning influence of the institutional investment environment is most likely explained by our particular measure which captures the risk to foreign investors. Although a risky environment for foreign investors might also be one which inhibits investments by domestic actors, it is less clear that the factors captured by the investment profile measure should have as great an impact on spillovers from imports as foreign investment. Unfortunately, in the absence of a comparable measure of risks faced by domestic firms, we cannot definitely say whether similar institutional attributes mediate import-weighted CO_2-efficiency spillovers.

Notwithstanding these differences, our statistical findings strongly support the thesis that domestic attributes matter in influencing the degree to which higher CO_2-efficiency in one country spills-over to raise CO_2-efficiency in other countries to which it is linked. That is, international spillovers not only depend on the existence of economic ties with more CO_2-efficient countries, but on domestic attributes influencing countries' ability to "capture" these spillovers. Accordingly, in modelling the degree to which CO_2-efficiency enhancing innovative efforts (R&D, etc.) spillover across national borders, we suggest that analysts should take account of cross-national differences in existing levels of (in)efficiency, education and the institutional environmental for investment (Bosetti et al. 2009; De Cian 2007; Grubb et al. 2002). Assuming that all countries are equally-placed to capture international CO_2-efficiency spillovers is an over-simplification of a more complex, geographically contingent reality.

Moreover, echoing work which highlights the importance of particular enabling conditions for transferring, acquiring and absorbing climate mitigation technologies (IPCC 2000, 2007; UNFCCC n.d.), our results indicate that improving domestic CO_2-efficiency may be accelerated by policies which create fertile domestic conditions for appropriating international CO_2-efficiency spillovers. Specifically, interventions which increase the share of the adult workforce who are educated and reduce the risks to foreign investors should enhance countries' capacity to capture efficiency-enhancing spillovers via imports and FDI, respectively. We cannot rule out the possibility that the very same policies will result in higher per capita emissions or, more generally, that gains in domestic CO_2-efficiency will be sufficient to counteract the effects of rising scale (Peters et al. 2007). Yet, to the extent that increases in CO_2-efficiency are central to realising the goals of climate stabilisation (IPCC 2007; Ürge-Vorsatz and Metz 2009), our study provides novel insights into the conditions under which countries are most likely to benefit from CO_2-efficiency enhancing international spillovers.

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Table 1. Summary descriptive statistical variable information.

	Mean	Std. Dev.	Min	Max
$\ln y_{it}$	1.081	0.596	-0.464	3.219
$\ln y_{it-1}$	1.078	0.603	-0.464	3.219
$GDPpc_{it}$	8.841	1.042	6.179	10.557
$\%indust_{it}$	31.253	8.281	6.846	62.160
edu_{it}	7.153	3.107	0.377	12.951
$invprof_{it}$	7.219	2.278	0.000	12.000
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1}$	0.810	0.140	0.274	1.313
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1}$	0.754	0.217	0.119	1.371
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$	0.895	0.539	-0.358	2.828
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$	0.807	0.506	-0.315	2.797
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$	5.764	2.688	0.235	12.557
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$	5.477	2.993	0.124	15.131
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot invprof_{it}$	5.925	2.362	0.000	12.774
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot invprof_{it}$	5.610	2.784	0.000	16.083

Table 2. Estimation results.

	(1)	(2)	(3)
$\ln y_{it-1}$	0.559**	0.771**	0.681**
	(0.0466)	(0.0695)	(0.0735)
$GDPpc_{it}$	0.300**	0.257**	0.186**
	(0.0712)	(0.0557)	(0.0410)
$\%indust_{it}$	-0.00326*	-0.00445**	-0.00407**
	(0.00145)	(0.00137)	(0.00135)
edu_{it}	-0.0276	-0.0189	-0.0516*
	(0.0326)	(0.0262)	(0.0229)
$invprof_{it}$	-0.00443**	-0.00301	-0.00519
	(0.00172)	(0.00206)	(0.00931)
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1}$	0.331**	0.161*	-0.280
	(0.0815)	(0.0810)	(0.175)
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1}$	-0.00729	0.115**	0.0150
	(0.0366)	(0.0398)	(0.112)
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$		-0.0888	0.0318
		(0.0708)	(0.0696)
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$		-0.0881**	-0.111**
		(0.0323)	(0.0406)
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$			0.0686**
			(0.0199)
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$			-0.0116
			(0.00789)
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot invprof_{it}$			-0.0206
			(0.0118)
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot invprof_{it}$			0.0274**
			(0.00937)
Observations	1271	1271	1271
Number of countries	77	77	77

Appendix. List of countries included in study.

Algeria, Argentina, Australia, Austria, Bangladesh, Belgium, Bolivia, Brazil, Bulgaria, Cameroon, Canada, Chile, China, Colombia, Costa Rica, Cote d'Ivoire, Cyprus, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Ethiopia, Finland, France, Gabon, Germany, Ghana, Greece, Guatemala, Honduras, Hungary, India, Indonesia, Iran, Ireland, Italy, Jamaica, Japan, Jordan, Kenya, Korea (Rep.), Malaysia, Mexico, Morocco, Mozambique, Myanmar, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Panama, Paraguay, Peru, Philippines, Portugal, Romania, Senegal, Singapore, South Africa, Spain, Sudan, Sweden, Switzerland, Syrian Arab Republic, Tanzania, Thailand, Trinidad and Tobago, Tunisia, Turkey, United Kingdom, United States, Uruguay, Venezuela, Zambia, Zimbabwe.