Climatic Change (2012) 112:469–491
DOI 10.1007/s10584-011-0204-8

Do recipient country characteristics affect international spillovers of CO_2-efficiency via trade and foreign direct investment?

Richard Perkins · Eric Neumayer

Received: 4 August 2009 / Accepted: 1 August 2011 / Published online: 27 August 2011

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 spatial dependence 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 higher institutional quality. We find that less CO_2-efficient countries and countries with higher institutional quality experience stronger FDI-weighted CO_2-efficiency spillovers, whereas a higher level of human capital increases receptivity to import-weighted international spillovers.

1 Introduction

Within debates about how globalization affects countries' greenhouse gas (GHG) 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 GHG efficiency-enhancing technologies, policies and performances found in one economy diffuse ("spillover") into another economy via transnational economic linkages (Grubb et al. 2002; Leimbach and Baumstark 2010; Stern 2007). Recent work has lent some support to the existence of international spillovers, finding that countries which import a larger share of their goods from economies which are more CO_2-efficient (that is, which generate less CO_2 per unit of economic activity) are themselves more CO_2-efficient,

R. Perkins (✉) · E. Neumayer
Department of Geography and Environment and The Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, Houghton Street, London WC2A 2AE, UK
e-mail: r.m.perkins@lse.ac.uk

E. Neumayer
e-mail: e.neumayer@lse.ac.uk

indicating that foreign GHG-efficiency improvements can spread across borders (Perkins and Neumayer 2008, 2009). An important corollary is that economic integration may, at least measured in terms of CO_2-efficiency, contribute to the goals of climate mitigation. Moreover, such findings suggest that policies which promote external liberalization may accelerate improvements in domestic CO_2-efficiency, notably where countries expand their economic ties with more CO_2-efficient countries.

Missing from this work on international spillovers, however, has been any attempt to investigate whether attributes of recipient countries influence the degree to which higher foreign CO_2-efficiencies spillover across borders to raise domestic CO_2-efficiency. That is, the literature says very little about whether all countries "gain" equally from higher CO_2-efficiencies in foreign countries to which they are linked economically, or whether some countries are better placed than others to take advantage of efficiency-enhancing international spillovers. The implicit assumption in past research has been that what matters is simply the type of connectivity with other countries and levels of CO_2-efficiency in these countries. Yet there are compelling reasons to suspect that characteristics of the focal recipient country might well influence the degree to which higher CO_2-efficiency in foreign economies may spillover domestically via transnational economic linkages.

The basic idea that domestic characteristics of recipient countries influences their ability to take advantage of efficiency-enhancing foreign technological knowledge has long been recognized in theoretical accounts of income convergence and productivity catch-up (Abramovitz 1986; Fagerberg 1994; Nelson and Phelps 1966). Importantly, these theoretical predictions might also be expected to apply to CO_2-efficiency spillovers, because the latter are similarly likely to depend on countries' ability to make productive use of foreign knowledge. Empirically, too, the notion that domestic characteristics affect the cross-national diffusion of productivity-enhancing technology receives some support in the literature (Coe et al. 2008; Fagerberg 1994; Keefer and Knack 1997). Again, to the extent that technical efficiency-based productivity gains may raise CO_2-efficiency, these studies similarly suggest that attributes of recipient countries should influence the degree of international CO_2-efficency spillover.

Our goal in the present article is to explore the hitherto neglected issue of how domestic characteristics in recipient countries affect international CO_2-efficency spillovers. We focus, in particular, on two sets of domestic attributes: (a) existing levels of domestic CO_2-efficiency; and (b) social capabilities, defined here in terms of human capital and institutional quality. Motivating our focus on these attributes is that they have been identified in past theoretical and empirical work as domestic characteristics influencing general foreign productivity spillovers and income catch-up. 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 studies which have 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 attributes mediate international 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 higher level of institutional quality experience stronger inward FDI-weighted CO_2-efficiency spillovers, whereas a better educated workforce increases domestic receptivity to import-weighted international CO_2-efficiency spillovers. Thus, while different attributes matter, recipient 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). Note, this particular conception of spillovers is markedly more expansive than the one in the mainstream literature on technological change, which mainly focuses on so-called knowledge spillovers (Keller 2004). Knowledge spillovers are positive externalities that arise from the quasi-public good characteristics of technological knowledge. They take place when technological knowledge diffuses from one actor to another actor, but where the innovator/owner of the technology is not fully compensated for this transfer by the user (Popp 2006).

Remaining with the wider conception of international spillovers, recent literature has assumed that efficiency-enhancing technological efforts diffuse cross-nationally, both in embodied (i.e. physical plant and equipment) and disembodied (i.e. know-how, know-why, etc.) form (IPCC 2007; Nagashima and Dellink 2008). The cross-national spread of new technology is said to be important in realizing climate mitigation goals for two reasons. First, technology plays a central role in improving domestic CO_2-efficiency, and can therefore potentially counteract the emissions-enhancing effects of increased 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 (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 through market transactions, e.g. via the purchase of equipment from foreign vendors, licensing agreements, or internal transfers of new technology from a transnational corporation's (TNC's) parent to its overseas subsidiary. Potentially more significant still, technology transfer may take place indirectly as a by-product of these market transactions in the form of knowledge spillovers, described above (Keller 2004). Knowledge spillovers may come about in various ways—including labor turnover, demonstration effects and vertical linkages between firms (Saggi 2002)—and potentially allow local actors to appropriate efficiency-enhancing technological knowledge from foreign innovators at a fraction of the original R&D costs.

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 dependence[1] 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

[1] By spatial dependence, we mean that choices of actors in one spatial unit depend on the choices of actors in other spatial units.

promotional policies supporting the uptake of new renewables in electricity generation (OECD 2008).[2]

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 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 outcome, policy or practice in other countries is a determinant of the same outcome, policy or practice in a focal economy, and therefore the extent to which behaviours, performances and innovations diffuse across borders via transnational linkages. Using this spatial econometric approach, Perkins and Neumayer (2008, 2009) find evidence for spillovers in CO_2-efficiency. 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 analyze whether domestic attributes influence the degree of spillover in CO_2-efficiency. 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 recipient 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 general 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 dependence (the strength of spillover): (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 into higher domestic CO_2-efficiency.

[2] 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 (IPCC 2007). 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.

3.1 Relative backwardness (the "inefficiency" thesis)

The idea that relative inefficiency or backwardness[3] 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-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 (Perkins and Neumayer 2005).

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 CO_2-efficient countries[4] (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)

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 (Lall 1992).

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; Nelson and Phelps 1966). Human capital, in turn, better-allows domestic firms to respond to competitive pressures from more productive foreign competitors by upgrading their technologies.

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

[4] 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.

Another commonly discussed aspect of social capability is the institutional environment. Within this broad category, a wide range of domestic attributes have been mentioned, including corruption, bureaucratic quality, rule of law, security of property rights, and “the ease of doing business” (Coe et al. 2008; Keefer and Knack 1997). A common feature of arguments which emphasise institutional aspects is the assumption that a country’s level of institutional quality, broadly understood, affects the risk of doing business for both domestic and foreign producers. Institutional quality 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 2011). 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) with a higher level of institutional quality.

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—over the degree of CO_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.

Starting with 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. However, they are suggestive at best, and say nothing about the importance of capabilities in influencing the degree of cross-national CO_2-efficiency spillovers.

A much larger body of work has examined general knowledge spillovers, that is, spillovers affecting general economic productivity rather than specifically productivity gains directly affecting CO_2-efficiency. Several of these studies lend weight to the idea that less efficient countries gain more (i.e. in terms of higher domestic efficiency) from foreign technological knowledge 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 et al. 1996; Girma et al. 2001; Dimelis 1995) and/or poorer countries (Crespo et al. 2004) benefit less from foreign knowledge 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). That is, countries with both very high and very low levels of relative efficiency and wealth would appear to benefit more from productivity spillovers than countries with medium levels of these characteristics. Making sense of these divergent findings is difficult. However, it is acknowledged that they are a product of different samples (of countries, sectors and firms), measures and analytical methods, suggesting that empirical inferences regarding the relationship between relative efficiency and productivity spillovers are sensitive to the research design (Keller 2004; Saggi 2002).

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 foreign productivity spillovers are positively correlated with levels of human capital (Coe et al. 2008; Crespo et al. 2004; 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 (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 foreign knowledge 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, bureaucratic quality, corruption, contract enforceability and constraints on the executive (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 in constant US$ of 2000 on a purchasing power parity (PPP) basis. Data for both CO_2 emissions and GDP are taken from IEA (2008). The unit of observation is the country year. Our global sample comprises 77 (developed and developing) countries listed in the Appendix over the period 1982–2005, with coverage being limited only by the availability of data.

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). 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 artifacts (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, more efficient technology may stimulate indigenous 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 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.[5] 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 (Eaton and Kortum 1996; Falvey et al. 2004). In order to construct our import-weighted spatial lag variable, we use data from UN (2009) on machinery and manufactured goods imports of focal country i from foreign countries k as the connectivity variable.

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). Through their investments in host economies, TNCs from more CO_2-efficient economies may transfer advanced, carbon-efficient technologies and organizational practices directly, incorporating them in process equipment, or engineering them into their products (Mielnik and Goldemberg 2002; OECD 1997; Prakash and Potoski 2007). The motivation for doing so is that ownership-specific advantages, in terms of superior technologies, may provide subsidiaries and affiliates with an ability to compete in host economies. As acknowledged in the literature, operating in foreign countries involves additional costs arising from the 'liability of foreignness' (Hymer 1976), meaning that TNCs must have additional compensating advantages over domestic firms who have advantages of their own (Saggi 2002).

Indirectly, the presence of TNCs may give rise to knowledge spillovers, as domestic firms learn from knowledge embedded in the technologies and practices operated by their foreign rivals (Facundo et al. 2009). However, it should be pointed out that spillovers are by no means guaranteed, and the internationalization of ownership-specific advantages via direct investments in fully-owned subsidiaries may be used by transnationals in order to protect their proprietary knowledge (Saggi 2002). The involvement of TNCs from more CO_2-efficient countries may additionally give rise to increased price and/or quality competition which incentivises indigenous firms to invest in more modern, efficient technologies and, moreover, raises average levels of CO_2-efficiency by forcing inefficient firms out of business (Ang 2009).

Empirical support for the influence of FDI is 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

[5] Note, Cole (2006) finds that trade intensity (the ratio of imports and exports to GDP) is positively correlated with energy-intensity in a sample of developed and developing countries, although this study is based on a sectorally and geographically aggregated trade measure.

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 (2010) 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 general productivity spillovers literature (Hejazi and Safarian 1999; Pottelsberghe de la Potterie and Lichtenberg 2001). If anything, evidence for productivity spillovers from FDI is weaker in developing countries (Javorcik 2008), which might explain the results from the studies of Hübler and Keller (2010) and Perkins and Neumayer (2009). Our FDI-weighted spatial lag measure is constructed using bilaterally disaggregated data from UNCTAD on the stock of inward foreign direct investment in country i originating from countries k as the connectivity variable. Note, these data are not freely available to the public, but were acquired by the authors in exchange for a considerable financial contribution to UNCTAD.

While FDI and imports of machinery and manufactured goods are plausible channels to transmit CO_2-efficiency improvements, there could be other channels that similar to FDI and imports are correlated with spatial proximity between countries. This could pose an identification problem if our FDI- and import-weighted spatial lag variables spuriously pick up a spillover effect that simply works via spatial proximity. In separate estimations (not reported below), we have therefore included a further spatial lag variable with reversed distance between countries as the connectivity matrix. While coefficient sizes change somewhat, as one would expect, our results are robust to the inclusion of this additional spatial lag in the sense that the pattern of interaction effects between the spatial lag variables and domestic attributes of recipient countries remains the same as without this distance-weighted spatial lag variable included.

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 analyzing 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 (LDV).[6] Consistent with 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

[6] Note that while this variable seemingly measures absolute 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-efficiency and, thus, in effect measures relative backwardness.

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 average number of years of schooling received by the population aged 25 and above. These data are linearly interpolated between the available 10 year intervals.

Another category of social capability explored in the present study is institutional quality—also widely discussed under the rubric of good governance. From a theoretical perspective, by influencing the degree of business risk, institutional quality should affect the 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.

We selected our measure of institutional quality on the basis that it should capture broad and comprehensive governance attributes which influence both domestic and foreign investor firms' decisions to make efficiency-enhancing investments and, moreover, in ways that affect the degree of spillover from the spatial lag variables. Accordingly, we decided to construct a variable that measures the unweighted mean of a country's value on bureaucratic quality, rule of law and the absence of corruption, as published by the *International Country Risk Guide* (PRS 2009). The composite measure runs from 0–6, with 0 representing the lowest level of institutional quality, and 6 the highest.

Inadequate institutions should not only reduce the overall volume of foreign direct investment. They might also plausibly reduce the CO_2-efficiency enhancing content of FDI. Where institutional quality is lower, property rights will be less secure, potentially negatively impacting the revenue stream from investments (Keefer and Knack 1997). For instance, in a country with a weak rule of law, investors may fear that new governments may change the terms of an existing contract (e.g. for the supply of electricity from a power plant). Importantly, these risks are likely to make foreign investors less willing to commit resources to high-value investments, including those in modern, innovative process or product technologies (Fosfuri 2004). This is significant to the extent that many such advanced, capital-intensive technologies frequently embody higher levels of carbon-efficiency (Perkins 2007). Lower levels of institutional quality might also jeopardize the returns from investments in domestic learning, such as reverse engineering, reducing the incentives for indigenous firms to engage in technological efforts required to appropriate CO_2 efficiency-enhancing knowledge spillovers from the local presence of TNCs.

Along similar lines, a country's institutional quality might also affect CO_2 efficiency-enhancing spillovers from imports of machinery and manufactured goods. Again, factors such as corruption, a weak rule of law and poor quality government administration may negatively impact the predictability of returns from long-term investments in advanced, process-efficient and capital-intensive imported machinery. As a result, domestic actors are more likely to act conservatively by purchasing older, less capital-intensive equivalents, or simply continuing to operate existing, obsolete technology. Additionally, a poor institutional environment is one in which less efficient firms continuing to use obsolete—and CO_2-inefficient—technologies are more likely to survive, e.g. because rent seeking enterprises are sheltered from competition by protective government policies (Keefer and Knack 1997). Under these conditions, acquiring advanced, capital-intensive technologies from abroad may not be economically worthwhile, with firms potentially preferring to retain existing obsolete capital stock with lower levels of CO_2-efficiency. Likewise, where inadequate institutions increase investment risks, financial institutions (e.g. commercial banks) may be unwilling to lend to firms wishing to acquire imported technologies with higher up-front costs. Again, because of their vintage and process-efficiency, it is likely that these are precisely the technologies which embody higher levels of carbon-efficiency (Perkins 2007). As in the case of FDI, poor quality institutions might also be expected to reduce the sorts of investments required to make productive use of imported foreign technologies, and moreover take advantage of associated knowledge spillovers.

5.3 Control variables

We include the share of industry in value added, using data from World Bank (2008), to control for the fact that more industry-intensive economies should, all else equal, be less CO_2-efficient. 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 control for the share of fossil fuels in total domestic energy production (IEA 2010). The price of hydrocarbon-based energy is likely to be negatively correlated with the domestic share of fossil fuels, leading to higher demand for fossil fuel energy sources in countries where a greater amount of domestic energy production is made-up by carbon-carrying fuels. This, in turn, should result in lower levels of CO_2-efficiency. Data are taken from EIA (2010).

We also include GDP per capita, sourced form EIA (2008), in constant US$ of 2000 on a purchasing power parity basis 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, while Table 2 shows a bivariate correlation matrix.

5.4 Model and estimator

We estimate variants of the following model:

$$\begin{aligned}
\ln y_{it} = {} & \alpha_i + \beta_1 \ln y_{it-1} + \beta_2 \ln GDP\,per\,capita_{it} + \beta_3 \%industry_value_added_{it} \\
& + \beta_4 \%fossil_energy_prod_{it} + \beta_5 edu_{it} + \beta_6 inst_quality_{it} \\
& + \beta_7 \sum_k {w^{imp}}_{ikt-1} \ln y_{kt-1} + \beta_8 \sum_k {w^{FDI}}_{ikt-1} \ln y_{kt-1} \\
& + \beta_9 \sum_k {w^{imp}}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1} + \beta_{10} \sum_k {w^{FDI}}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1} \\
& + \beta_{11} \sum_k {w^{imp}}_{ikt-1} \ln y_{kt-1} \cdot edu_{it} + \beta_{12} \sum_k {w^{FDI}}_{ikt-1} \ln y_{kt-1} \cdot edu_{it} \\
& + \beta_{13} \sum_k {w^{imp}}_{ikt-1} \ln y_{kt-1} \cdot inst_quality_{it} + \beta_{14} \sum_k {w^{FDI}}_{ikt-1} \ln y_{kt-1} \cdot inst_quality_{it} + \delta_t + u_{it}
\end{aligned} \tag{1}$$

Where i represents the country under observation, k ($\neq i$) represents other countries, t is time, y_{it} is the dependent variable, the α_i represent country-specific fixed effects, $\ln y_{it-1}$ is the

Table 1 Summary descriptive statistical variable information

	Mean	Median	Std. Dev.	Min	Max
$\ln y_{it}$	1.082	1.022	0.596	−0.464	3.219
$\ln y_{it-1}$	1.079	1.022	0.603	−0.464	3.219
$\ln GDP\,per\,capita_{it}$	8.839	8.768	1.031	6.179	10.557
$\%industry\_value\_added_{it}$	31.413	30,759	8.328	6.247	62.160
$\%fossil\_energy\_prod_{it}$	0.491	0.566	0.381	0.000	1.000
edu_{it}	7.080	6.893	3.116	0.345	12.951
$inst\_quality_{it}$	3.723	3.333	1.423	0.667	6.000
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1}$	0.798	0.795	0.146	0.250	1.313
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1}$	0.724	0.739	0.237	0.119	1.371
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$	0.883	0.825	0.537	−0.358	2.828
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$	0.776	0.708	0.504	−0.315	2.797
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$	5.619	5.357	2.688	0.167	12.557
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$	5.236	4.776	3.032	0.113	15.131
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot inst\_quality_{it}$	2.946	2.782	1.199	0.402	6.104
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot inst\_quality_{it}$	2.733	2.568	1.407	0.159	8.041

temporally LDV, $GDP\,per\,capita_{it}$ is a country's per capita income, $\%industry\_value\_added_{it}$ its industrial share of GDP, $\%fossil\_energy\_prod_{it}$ is the share of fossil fuels in domestic energy production, edu_{it} is the level of a country's human capital, $inst\_quality_{it}$ is a country's institutional quality, $\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1}$ and $\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1}$ represent the two spatial lag variables, the δ_t represent year-specific fixed effects and u_{it} is the error term.

The country-specific fixed effects account for unobserved country differences influencing domestic CO_2-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 in technology, fossil fuel prices and other relevant factors that approximately affect equally all countries in the sample. Country- and time-specific fixed effects, together with the temporally LDV, 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 2010).

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 LDV 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 LDV 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

Table 2 Bivariate correlation matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1: $\ln y_{it}$	1.00														
2: $\ln y_{it-1}$	0.99	1.00													
3: ln $GDP\ per\ capita_{it}$	−0.36	−0.37	1.00												
4: $\%industry\_value\_added_{it}$	−0.50	−0.50	0.21	1.00											
5: $\%fossil\_energy\_prod_{it}$	−0.53	−0.53	0.17	0.45	1.00										
6: edu_{it}	−0.43	−0.44	0.84	0.14	0.17	1.00									
7: $inst\_quality_{it}$	−0.37	−0.38	0.79	0.09	0.09	0.75	1.00								
8: $\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1}$	0.25	0.25	0.02	−0.11	−0.12	−0.06	−0.11	1.00							
9: $\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1}$	−0.04	−0.04	0.11	−0.06	−0.02	0.15	0.11	0.54	1.00						
10: $\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$	0.93	0.94	−0.31	−0.46	−0.49	−0.40	−0.37	0.52	0.12	1.00					
11: $\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$	0.78	0.79	−0.24	−0.43	−0.42	−0.27	−0.23	0.48	0.51	0.84	1.00				
12: $\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$	−0.29	−0.30	0.78	0.07	0.11	0.91	0.64	0.33	0.34	−0.17	−0.07	1.00			
13: $\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$	−0.31	−0.32	0.71	0.04	0.10	0.84	0.60	0.25	0.60	−0.22	0.04	0.91	1.00		
14: $\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot inst\_quality_{it}$	−0.23	−0.24	0.75	0.02	0.02	0.67	0.88	0.34	0.37	−0.12	0.02	0.77	0.71	1.00	
15: $\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot inst\_quality_{it}$	−0.25	−0.26	0.65	−0.01	0.02	0.63	0.76	0.29	0.68	−0.16	0.15	0.70	0.84	0.88	1.00

autocorrelation in the first-differenced idiosyncratic errors. This can be tested and results fail to reject this assumption (to save space, the test results are not shown in the estimation table). 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 of six.

6 Results

Table 3 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 (model 1). As anticipated, we find evidence for conditional convergence in that the coefficient of the temporally LDV minus one is statistically significantly negative throughout,[7] 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. Regarding the control variables, as anticipated we find that richer countries have higher domestic CO_2-efficiency, whereas countries with a higher share of industry in value added and those with a higher share of fossil to total domestic energy production have lower efficiency. Conversely, we find that our education measure has no statistically significant influence by itself, and the institutional quality measure has an unexpected negative impact on domestic CO_2-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 associated with domestic CO_2-efficiency, a result which mirrors the ones 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. It is also in line with Hübler and Keller (2010) who find no statistically significant relationship between inflows of FDI and energy-intensity, again for a sample of developing countries. The estimated short-run degree of spatial dependence via imports is moderately strong at roughly 0.3. That is, a one percent increase in import-weighted foreign CO_2-efficiency is associated with a rise in domestic CO_2-efficiency of approximately 0.3% in the short-run and approximately 0.6% in the long-run.

An important question is whether the insignificant result for the spatial lag variable weighted by inward FDI stocks arises because there are important conditioning effects not captured by the specification of model 1. In model 2, we interact the spatial lag variables with domestic efficiency lagged by one period. The spatial lag variables are now constituent

[7] This cannot be directly observed from Tables 1 and 2, but follows from the confidence intervals of the estimated coefficients. To see why this implies conditional convergence, note that the growth rate of a variable is equivalent to the natural log of a variable minus its natural log one previous period. Hence, regressing the log-level on the lagged log-level is equivalent to regressing the growth rate on the log-level lagged by one period. The only difference is that the estimated coefficient of the growth rate equation is that of the log-level equation minus one. In the growth rate equation convergence is detected if the coefficient of the log-level lagged by one period is negative and statistically significant – more backward countries see faster growth in CO_2-efficiency. In the log-level equation convergence is detected if the coefficient of the lagged log-level minus one is negative and statistically significant.

Table 3 Estimation results

	Model 1	Model 2	Model 3	Model 4
$\ln y_{it-1}$	0.496***	0.695***	0.504***	0.527***
	(0.0515)	(0.0600)	(0.0527)	(0.0496)
$GDP\ per\ capita_{it}$	0.280***	0.238***	0.242***	0.195***
	(0.0643)	(0.0521)	(0.0546)	(0.0629)
$\%industry\_value\_added_{it}$	−0.00268**	−0.00380***	−0.00337***	−0.00284**
	(0.00130)	(0.00121)	(0.00129)	(0.00122)
$\%fossil\_energy\_prod_{it}$	−0.329***	−0.254***	−0.280***	−0.293***
	(0.0945)	(0.0783)	(0.0789)	(0.0877)
edu_{it}	−0.0340	−0.0268	−0.0713**	−0.0249
	(0.0321)	(0.0257)	(0.0303)	(0.0268)
$inst\_quality_{it}$	−0.0210**	−0.0205**	−0.0125	−0.0445*
	(0.00978)	(0.00950)	(0.00840)	(0.0253)
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1}$	0.307***	0.136*	−0.0615	0.248**
	(0.0698)	(0.0730)	(0.136)	(0.116)
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1}$	−0.00413	0.106***	−0.0137	−0.163**
	(0.0341)	(0.0351)	(0.0511)	(0.0672)
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$		−0.0651		
		(0.0524)		
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot \ln y_{it-1}$		−0.0779***		
		(0.0293)		
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$			0.0472***	
			(0.0182)	
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot edu_{it}$			0.00471	
			(0.00656)	
$\sum_k w^{imp}{}_{ikt-1} \ln y_{kt-1} \cdot inst\_quality_{it}$				−0.0112
				(0.0335)
$\sum_k w^{FDI}{}_{ikt-1} \ln y_{kt-1} \cdot inst\_quality_{it}$				0.0515***
				(0.0186)
Observations	1376	1376	1376	1376
Number of countries	77	77	77	77

Notes: Dependent variable is log of CO_2-efficiency. * Significant at 10% level, ** at 5% level, *** at 1% level

terms of an interaction effect and their coefficients merely represent the marginal effect of spatial dependence where the value of the conditioning variable (here, the temporally LDV) is zero. 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. However, note that in interaction models the marginal effects of variables are more complicated, as are their standard errors. Using the formulas in Brambor et al. (2006), the computed marginal effects and standard errors never suggest a statistically significant interaction effect for import-weighted spatial dependence. The (short-run) marginal effect of FDI-weighted spatial dependence can be estimated as 0.106–0.0779*$\ln y_{it-1}$, i.e. the marginal effect is a function of the values of the temporally LDV. At the minimum of the temporally LDV, the marginal effect is calculated to be 0.14, but it is rapidly diminishing, and becomes statistically indistinguishable from zero just before the sample mean and median of the temporally LDV at a value of around one is reached. Figure 1 shows how the marginal effect of the FDI-weighted spatial lag variable changes as the value of the temporally LDV increases. This result is consistent with theoretically-derived predications from models of relative backwardness, catch-up and convergence.

In model 3, we analyze the effect of interacting the spatial lag variables with the educational variable. As illustrated in Fig. 2, we find that the level of human capital has a positive impact on the degree of import-weighted spillover and the marginal effect becomes statistically significant beyond 4 years of schooling among the population aged 25 or above (note, roughly three quarters of observations in our sample have a human capital stock higher than 4 years). 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. One possible explanation for this result is that firms are more likely to use FDI to restrict the scope of knowledge spillovers (Mansfield and Romeo 1980). Hence human capital, which is understood to be important in taking advantage of these possible positive knowledge externalities, may logically be less relevant.

In model 4, we analyze the conditioning effect of institutional quality on spatial dependence. The coefficient for the inward FDI-weighted spatial lag interacted with our institutional quality measure is positive and statistically significant. The equivalent coefficient for the import-weighted spatial lag, however, fails to achieve statistical significance and further analysis of the marginal effect and its standard error confirmed the absence of an interaction. Hence higher institutional quality in the recipient country 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. Yet institutional quality does not increase the strength of international spillover via import-weighted linkages with more CO_2-efficient countries. Interestingly, Fig. 3 shows that the marginal effect of the FDI-weighted spatial lag variable is statistically significantly negative

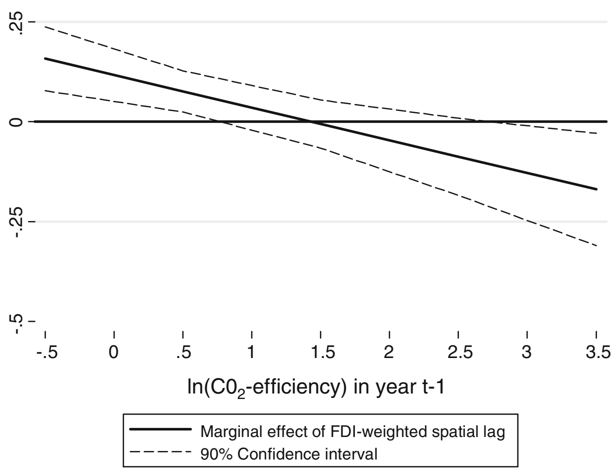

Fig. 1 Marginal effect of FDI-weighted spatial lag on CO_2-efficiency as the value of the temporally LDV changes. Note: Dependent variable is ln CO_2-efficiency

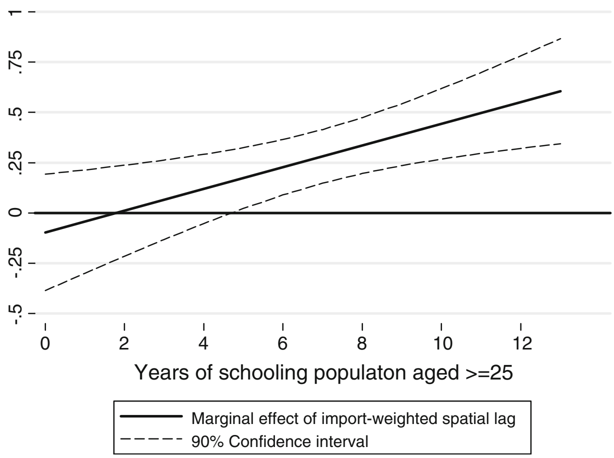

Fig. 2 Marginal effect of import-weighted spatial lag on CO_2-efficiency as the value of human capital changes. Note: Dependent variable is ln CO_2-efficiency

at low levels of institutional quality until a value of about 2, which is at the lowest decile of the distribution. It then becomes indistinguishable from zero until a value of slightly above 4 is reached, which is slightly above the mean, from when on it becomes statistically significantly positive and rising with further increases in institutional quality. What this implies is that there are negative FDI-weighted spillover effects on CO_2-efficiency in countries with very poor institutional quality, no spillover effects in the countries in the middle, and positive spillover effects in countries with high institutional quality.

The absence of positive FDI spillovers in countries with lower levels of institutional quality could be the product of a number of factors. Either fearing that they cannot protect their high-value knowledge-based assets from local imitation, or will not receive higher long-run returns from capital-intensive investments in advanced equipment, TNCs may be inclined to transfer their older CO_2-inefficient technologies to host countries with inadequate institutions. Moreover, where TNCs do transfer advanced technologies, they may restrict the scope of knowledge spillovers by taking extra precautions to protect their proprietary technology from imitation (e.g. enhanced secrecy clauses in employee contracts). Low levels of institutional quality may also reduce the incentives for local firms to invest in technological efforts to exploit FDI-related spillovers. These dynamics, which restrict the scope of efficiency-enhancing technological change, may be especially pronounced in host economies with extremely low levels of institutional quality. In such environments, inward FDI from CO_2-efficient economies may therefore actually reduce the CO_2-efficiency of the host economy. In well-governed countries, the reverse is likely to be true, which might explain the positive relationship between CO_2-efficiency spillovers and institutional quality at high values. Assured that contracts will be honored, and so on, TNCs may opt to transfer advanced, capital-intensive technologies with higher levels of CO_2-efficiency to host economies. Likewise, they should show a greater preference for modes of FDI which increase the scope for knowledge spillovers to domestic firms, such as joint-ventures. A secure institutional environment is also one in which local firms are more likely to enjoy positive returns from investments in capturing these positive externalities, incorporating efficiency-enhancing innovations into their process and product technologies, thereby contributing to wider improvements in CO_2-efficiency in host economies.

We refrain from presenting a model that combines all of the interactions in a single model. Braumoeller (2004) argues that with more than one interaction variable "tacit" interactions are created amongst the conditioning variables such that one should include a

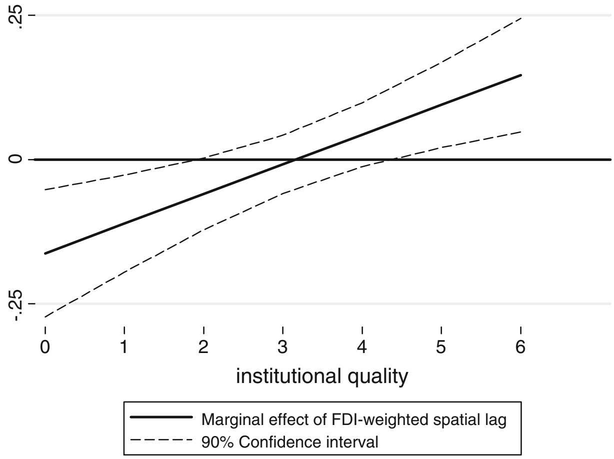

Fig. 3 Marginal effect of FDI-weighted spatial lag on CO_2-efficiency as the value of institutional quality changes. Note: Dependent variable is ln CO_2-efficiency

full set of interactions among all conditioning variables and all possible combinations of interactions between all conditioning and all variables of main interest. In the present context, this would mean adding another fourteen variables to the model, creating multicollinearity problems because some of the variables are highly correlated with each other.

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 in the recipient country – existing domestic CO_2-efficiency, human capital and institutional quality—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 improve their efficiency faster, which mirrors previous work which has similarly found evidence for cross-national convergence in CO_2-efficiency (Perkins and Neumayer 2008). However, the results reported here also advance on previous work. First, we find that countries with lower domestic CO_2-efficiency and countries with higher levels of institutional quality also experience stronger international spillovers from more CO_2-efficient foreign countries which are major direct investors in the host economy. Perkins and 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 stronger in less CO_2-efficient countries and in countries with higher institutional quality. Second, 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.

Although indicating that domestic attributes influence the strength of international spillovers in systematic 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). 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).

Apparent 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 domestic actors 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-weighted spillovers regarding the conditioning influence of institutional quality might be explained by the particular sensitivities of foreign investors to risk. Host economies with worse quality institutions are likely to be perceived as more risky, in the sense that the revenue streams from investments are less secure, making TNCs reluctant to transfer the sorts of knowledge- and capital-intensive technologies which are more CO_2-efficient. Additionally, owing to the enhanced (real or perceived) risks that transferred technological knowledge will be appropriated by local firms, TNCs may prefer to opt for modes of technology transfer which reduce the likelihood of efficiency-enhancing knowledge spillovers such as fully-owned subsidiaries. Indigenous importers of equipment and manufactured goods are likely to be less sensitive to institutional quality. Most importantly, because of their familiarity with the domestic institutional context, they might be expected to be more adept at managing and mitigating any business risks associated with inadequate institutions. The result: the weakness of domestic institutions should have less of an impact on the choices of imported technologies (notably those acquired by indigenous firms) than those transferred by TNCs. It is also worth noting that our particular measure of institutional quality is known to better reflect risks facing foreign investors than indigenous ones (Siddique and Williams 2008). Hence the disparity between FDI- and import-weighted CO_2-efficiency spillovers may therefore partly reflect our particular measure.

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 other countries spillovers domestically through transnational economic linkages. That is, international spillovers not only depend on the existence of economic ties with more CO_2-efficient countries, but on domestic attributes influencing recipient 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 institutional quality (Bosetti et al. 2009; De Cian 2007; Grubb et al. 2002; Leimbach and Baumstark 2010). Assuming that all countries are equally well placed to capture international CO_2-efficiency spillovers is an over-simplification of a more complex, geographically contingent reality.

Moreover, 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 economic agents by offering a higher institutional quality should enhance countries' capacity to capture efficiency-enhancing spillovers via imports and FDI, respectively. The former implies greater investment in primary and secondary schooling. The latter, reducing risks to economic agents, involves various reforms which promote good governance. That is, increasing domestic receptivity to international spillovers which improve domestic CO_2-efficiency calls for non-environmental policies, sometimes considered outside the remit of mainstream climate mitigation policies. To this extent, our findings reinforce the message of several studies, which emphasize the importance of generic government interventions—in the development of human capital and improving domestic institutional quality—in creating an enabling environment for the transfer, acquisition and absorption of GHG-friendly technologies (IPCC 2000, 2007; UNDP 2007; UNFCCC 2011; Rock et al. 2009).

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 in the recipient country will be insufficient 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.

Acknowledgements The authors would like to acknowledge the financial support of the UK's Economic and Social Research Council (ESRC), [grant number RES-000-22-27530]. We thank three anonymous referees, Ralph Martin, and participants at the 2010 Association of American Geographers and American Political Science Association meetings for their helpful and constructive comments.

Appendix: list of countries included in the 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.

References

Abramovitz M (1986) Catching up, forging ahead, and falling behind. J Econ Hist 46:385–406

Ang JB (2009) CO_2 emissions, research and technology transfer in China. Ecol Econ 68:2658–2665

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 58.

Bosetti V, Carraro C, Duval R, Sgobbi A, Tavoni M (2009) The role of R&D and technology diffusion in climate change mitigation: New perspectives using the WITCH model. OECD Economics Department Working Papers No.664. OECD publishing

Brambor T, Clark RC, Golder M (2006) Understanding interaction models: improving empirical analysis. Polit Anal 14:63–82

Braumoeller BF (2004) Hypothesis testing and multiplicative interaction terms. Int Organ 58:807–820

Busch PO, Jorgens H, Tews K (2005) The global diffusion of regulatory instruments: the making of a new international environmental regime. Ann Am Acad Pol Soc Sci 598:146

Castellani D, Zanfei A (2003) Technology gaps, absorptive capacity and the impact of inward investments on productivity of European firms. Econ Innovat New Tech 12:555–576

Coe DT, Helpman E, Hoffmaister AW (2008) International R&D spillovers and institutions. NBER Working Paper No. W14069

Cohen D, Soto M (2007) Growth and human capital: good data, good results. J Econ Growth 12:51–76

Cole MA (2006) Does trade liberalization increase national energy use? Econ Lett 92:108–112

Crespo J, Martín C, Velázquez FJ (2004) International technology spillovers from trade: the importance of the technological gap. Investigaciones Económicas 28:515–534

De Cian E (2007) International technology spillovers in climate-economy models: two possible approaches. Fondazione Eni Enrico Mattei Working Paper 85. Fondazione Eni Enrico Mattei, Milan

Dimelis S (1995) Spillovers from foreign direct investment and firm growth: technological, financial and market structure effects. International Journal of the Economics of Business 12:85–104

Eaton J, Kortum S (1996) Trade in ideas: patenting and productivity in the OECD. J Int Econ 40:251–278

Epstein M, Roy M-J (1998) Managing corporate environmental performance: a multinational perspective. Eur Manag J 16:284–296

Facundo A, Matthew AC, Robert JRE, Marco GE (2009) In search of environmental spillovers. World Econ 32:136–163

Fagerberg J (1994) Technology and international differences in growth rates. J Econ Lit 32:1147–1175

Falvey R, Foster N, Greenaway D (2004) Imports, exports, knowledge spillovers and growth. Econ Lett 85:209–213

Falvey R, Foster N, Greenaway D (2007) Relative backwardness, absorptive capacity and knowledge spillovers. Econ Lett 97:230–234

Findlay R (1978) Relative backwardness, direct foreign investment, and the transfer of technology: a simple dynamic model. Q J Econ 92:1–16

Fosfuri A (2004) Determinants of international activity: evidence from the chemical processing industry. Res Pol 33:1599–1614

Frantzen D (2000) R&D, human capital and international technology spillovers: a cross-country analysis. Scand J Econ 102:57–75

Gerschenkron A (1962) Economic backwardness in historical perspective: a book of essays. Belknap Press of Harvard University Press, Cambridge

Girma S, Greenaway D, Wakelin K (2001) Who benefits from foreign direct investment in the UK? Scot J Polit Econ 48:119–133

Golombek R, Hoel M (2005) Climate policy under technology spillovers. Environ Resource Econ 31:201–227

Griffith R, Redding S, Reenen JV (2004) Mapping the two faces of R&D: productivity growth in a panel of OECD industries. Rev Econ Stat 86:883–895

Grubb MJ, Hope C, Fouquet R (2002) Climatic implications of the Kyoto Protocol: the contribution of international spillover. Climatic Change 54:11–28

Hejazi W, Safarian AE (1999) Trade, foreign direct investment, and R&D spillovers. J Int Bus Stud 30:491–511

Hübler M, Keller A (2010) Energy savings via FDI? Empirical evidence from developing countries. Environ Dev Econ 15:59–80

Hymer SH (1976) The international operations of national firms: a study of direct investment. MIT, Cambridge
IEA (2008) CO_2 emissions from fuel combustion, 2008th edn. International Energy Agency, Paris
IEA (2010) World energy statistics and balances. IEA, Paris
IPCC (2000) Methodological and technological issues in technology transfer. Cambridge University Press, Cambridge
IPCC (2007) Climate change 2007: mitigation of climate change. Cambridge University Press, Cambridge
Javorcik BS (2008) Can survey evidence shed light on spillovers from foreign direct investment? World Bank Res Obs 23:139–159
Keefer P, Knack S (1997) Why don't poor countries catch up? A cross-national test of an institutional explanation. Econ Inq 35:590–602
Keller W (2004) International technology diffusion. J Econ Lit 42:752–782
Kokko A, Tansini R, Zejan MC (1996) Local technological capability and productivity spillovers from FDI in the Uruguayan manufacturing sector. Dev Stud 32:602–611
Lall S (1992) Technological capabilities and industrialisation. World Dev 20:165–186
Leimbach M, Baumstark L (2010) The impact of capital trade and technological spillovers on climate policies. Ecol Econ 69:2341–2355
Luken R, Van Rompaey F (2008) Drivers for and barriers to environmentally sound technology adoption by manufacturing plants in nine developing countries. J Clean Prod 16:S67–S77
Mansfield E, Romeo A (1980) Technology transfer to overseas subsidiaries by U.S-based firms. Q J Econ 95:737–750
Mauro P (1995) Corruption and growth. Q J Econ 110:681–712
Meyer KE, Sinani E (2009) When and where does foreign direct investment generate positive spillovers? A meta analysis. J Int Bus Stud 40:1075–1094
Mielnik O, Goldemberg J (2002) Viewpoint: Foreign direct investment and decoupling between energy and gross domestic product in developing countries. Energ Pol 30:87–89
Nagashima M, Dellink R (2008) Technology spillovers and stability of international climate coalitions. International Environmental Agreements: Politics, Law and Economics 8:343–365
Nelson RR, Phelps ES (1966) Investment in humans, technological diffusion, and economic growth. Am Econ Rev 56:69–75
Nickell S (1981) Biases in dynamic models with fixed effects. Econometrica 49:1417–1426
OECD (1997) Economic globalization and the environment. OECD, Paris
OECD (2008) Environmental policy, technological innovation and patents. OECD, Paris
Ohkawa K, Rosovsky H (1973) Japanese economic growth: trend acceleration in the twentieth century. Stanford University Press, Stanford
Peri G, Urban D (2006) Catching-up to foreign technology? Evidence on the "Veblen–Gerschenkron" effect of foreign investments. Reg Sci Urban Econ 36:72–98
Perkins R (2007) Globalizing corporate environmentalism? Convergence and heterogeneity in Indian industry. Stud Comp Int Dev 42:279–309
Perkins R, Neumayer E (2005) The international diffusion of new technologies: a multitechnology analysis of latecomer advantage and global economic integration. Ann Assoc Am Geogr 95:789–808
Perkins R, Neumayer E (2008) Fostering environment-efficiency through transnational linkages? Trajectories of CO_2 and SO_2, 1980–2000. Environ Plann A 40:2970–2989
Perkins R, Neumayer E (2009) Transnational linkages and the spillover of environment-efficiency into developing countries. Global Environ Change 19:375–383
Peters GP, Weber CL, Guan D, Hubacek K (2007) China's growing CO_2 emissions: a race between increasing consumption and efficiency gains. Environ Sci Technol 41:5939–5944
Peterson S (2008) Greenhouse gas mitigation in developing countries through technology transfer? A survey of empirical evidence. Mitigation and Adaptation Strategies for Global Change 13:283–305
Pitlik H (2007) A race to liberalization? Diffusion of economic policy reform among OECD-economies. Publ Choice 132:159–178
Plümper T, Neumayer E (2010) Model specification in the analysis of spatial dependence. Eur J Polit Sci 49:418–442
Popp D (2006) R&D subsidies and climate policy: is there a "free lunch"? Climatic Change 77:311–341
Pottelsberghe de la Potterie B, Lichtenberg F (2001) Does foreign direct investment transfer technology across borders? Rev Econ Stat 83:490–497
Prakash A, Potoski M (2007) Investing up: FDI and the cross-country diffusion of ISO 14001 management systems. Int Stud Q 51:723–744
PRS (2009) International country risk guide (ICRG). PRS, East Syracuse
Rock MT, Murphy JT, Rasiah R, van Seters P, Managi S (2009) A hard slog, not a leap frog: globalization and sustainability transitions in developing Asia. Technol Forecast Soc Change 76:241–254

Roodman D (2007) A short note on the theme of too many instruments. Working Paper No. 125. Center for Global Development, Washington, DC
Saggi K (2002) Trade, foreign direct investment, and international technology transfer: a survey. World Bank Res Obs 17:191–235
Siddique A, Williams A (2008) The use (and abuse) of governance indicators in economics: a review. Econ Govern 9:131–175
Sjöholm F (1999) Technology gap, competition and spillovers from direct foreign investment: evidence from establishment data. J Dev Stud 36:53–73
Stern N (2007) The economics of climate change: the Stern review. Cambridge University Press, Cambridge
UN (2009) Commodity trade statistics database (COMTRADE). United Nations Statistics Division, New York
UNCTAD (2007) World investment report: transnational corporations, extractive industries and development. United Nations, Geneva
UNDP (2007) Human development report 2007/2008. Fighting climate change. Human solidarity in a divided world. Palgrave, Basingstoke
UNFCCC (2011) Enabling environment. http://unfccc.int/ttclear/jsp/EEnvironment.jsp
Ürge-Vorsatz D, Metz B (2009) Energy efficiency: how far does it get us in controlling climate change? Energy Efficiency 2:87–94
Wang Y (2007) Trade, human capital, and technology spillovers: an industry-level analysis. Rev Int Econ 15:269–283
World Bank (2008) World development indicators. World Bank
Worrell E, Bernstein L, Roy J, Price L, Harnisch J (2009) Industrial energy efficiency and climate change mitigation. Energy Efficiency 2:109–123
Xu B, Chiang EP (2005) Trade, patents and international technology diffusion. J Int Trade Econ Dev 14:115–135
Xu B, Wang J (2000) Trade, FDI, and international technology diffusion. J Econ Integrat 15:585–601