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A Contribution to the Schumpeterian Growth Theory and Empirics

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Abstract This paper proposes an integrated theoretical and methodological framework characterized by technological interactions to explain growth processes from a Schumpeterian perspective. Global interdependence implied by international R&D spillovers needs to be taken into account in the theoretical model as well as in the empirical model. The spatial econometric methodology is the adequate tool to empirically deal with this issue. The econometric model we propose includes the neoclassical growth model as a particular case. We can therefore explicitly test the role of R&D investment in the long run growth process against the Solow growth model. Finally, the properties of our spatial econometric specification allow evaluating explicitly the impact of home and foreign R&D spillovers.

Keywords multi-country model · Schumpeterian growth · R&D spillovers · spatial econometrics

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"A generally unexplored possibility for studying cross-section dependence in growth (and other contexts) is to model these correlations structurally as the outcome of spillover effects." (Durlauf, Johnson and Temple, 2005)

1 Introduction

Is the real world growth process better explained by the neoclassical or the Schumpeterian growth theories? To the best of our knowledge, this question has not found a direct, clear and convincing answer in the growth literature. For the neoclassical model, factor accumulation and exogenous technological progress are the key determinants of the growth process. In contrast, for the Schumpeterian model, the growth process is based on endogenous profit driven knowledge accumulation and diffusion. The modeling strategy and econometric methodology traditionally used in the literature to estimate those models cannot help to discriminate between the two competing theories. On the one hand, empirical evidence found using the neoclassical growth model has often been interpreted to cast some doubt on endogenous growth models as also underlined by Howitt (2000). However, this cannot be considered as direct evidence against endogenous growth models. On the other hand, there seems to be a growing consensus view that technology adoption should be considered as endogenous in order to think about why the poorest countries in the world remain so poor. This view needs to be confronted to data using the appropriate econometric methodology and tested.

Our main contribution is to cast both models in an integrated theoretical and methodological framework and to propose a simple test of a generalized version of the multi-country Schumpeterian growth model based on the one elaborated by Howitt (2000) versus a multi-country Solow growth model (Solow, 1956) with imperfect technological interdependence similar to that proposed by Ertur and Koch (2007). Actually we show that the latter is nested in the former, once world-wide technological interdependence, well documented in the empirical literature (Keller, 2004), is explicitly modeled and estimated using the overlooked methodological tools of spatial econometrics (Anselin, 1988). Therefore, our generalized model can be interpreted as a Schumpeterian extension of the Solow growth model since in addition to factor accumulation, we show that innovation caused by R&D investment plays a major role in explaining the growth process. Our model includes both determinants, with technological diffusion occurring concretely between pairs of countries, human capital reflecting absorptive capacity along the lines of Nelson and Phelps (1966), and physical capital playing the usual role. More specifically, we show that when the R&D expenditures have no effect on the growth rate of technology, our multi-country Schumpeterian growth model reduces to the multi-country Solow growth model. The implied constraints may be easily tested and are actually rejected in our sample. Our integrated multi-country Schumpeterian growth model appears therefore as the best explanation of the growth process.

Explicit modeling of technological interdependence is then crucial to challenge the fundamental question raised in the growth literature and to elaborate a completely integrated theoretical as well as empirical framework. This is our specific contribution regarding the model proposed by Howitt (2000), which is, in our opinion, overly restrictive since complex interactions between countries are overlooked or oversimplified.[1]

[1] However, we acknowledge that Aghion and Howitt were aware of the limitations of the Howitt model (see footnote 23, p. 421, 1998).

Traditionally, empirical growth papers structurally derive econometric reduced forms from the neoclassical growth model along the lines of Mankiw *et al.* (1992), since it has some suitable properties, which facilitate its econometric estimation. Indeed, all countries have an identical long run growth rate implying that their long run growth paths are parallel. Another salient characteristic of this model is the fact that all countries have access to the same pool of knowledge (Mankiw, 1995). In contrast, earlier endogenous growth models do not share those theoretical properties and face some problems.

From the empirical perspective, Mankiw *et al.* (1992) argue that the neoclassical growth model with exogenous technological progress and diminishing returns to capital explains most of the cross-country variation in per worker output. Evidence of β-convergence in growth regressions (Barro and Sala-i-Martin, 2004) is often claimed to be consistent with neoclassical theory but not with endogenous growth theory. Evans (1996) shows that the dispersion of per capita income across advanced countries has exhibited no tendency to rise over the postwar era, as would be predicted by some endogenous growth models; instead, these countries have been converging to parallel growth paths of the sort implied by the neoclassical growth model with a common world technology.

Another major problem faced by endogenous growth models is that they are difficult to estimate since they imply that growth rates at steady state are endogenously determined by the level of income or by the current out-of steady state growth rate. Steady-state growth rates are therefore specific to each country and should be simultaneously estimated. In the neoclassical framework, this variable is assumed exogenous and identical for each country. Some authors, like Dinopoulos and Thomson (2000) for instance, propose to use simultaneous non-linear systems of equations to estimate Romer-Jones type of models (Romer, 1990; Jones, 1995), whereas Aghion and Howitt (1998) or Howitt (2000) propose to consider international diffusion of knowledge in the Schumpeterian growth model in order to estimate endogenous growth models. The latter approach has the interesting propriety to imply parallel long run growth paths, just like the neoclassical growth model, along with intentional actions taken by economic agents who respond to market incentives in order to accumulate new technology.

Therefore, in order to formulate an empirically tractable endogenous growth model encompassing the Solow model, we not only take Robert Solow seriously but we also take Philippe Aghion and Peter Howitt seriously. As a starting point, we consider the multi-country Schumpeterian growth model elaborated by Aghion and Howitt (1998) and Howitt (2000). Because of technology transfer, countries converge at long run to the same growth rate, which is the world growth rate. Therefore we can study the empirical implications of this model as we would do for the neoclassical growth model. However, in the neoclassical growth model, where each country is assumed to have the same technology and the same exogenous technical progress, the differences between countries around the technology path are random. In contrast, in the Schumpeterian growth model, where R&D expenditures are motivated by profit, the distribution of countries' technology depends on their R&D expenditures. Our contribution is to explicitly augment the research productivity function of endogenous growth models by adding a general process of technological interdependence similar to the one proposed by Ertur and Koch (2007). We assume that the productivity of R&D expenditures is low when countries are close to their own technology frontier and is high when countries are far from their own technology frontier, as also recently proposed by Aghion and Howitt (1998), Howitt and Mayer-Foulkes (2005) or Acemoglu *et al.* (2006) in order to take into account the "advantage of backwardness" (Gerschenkron, 1952) conferred on technological laggards. We show that this assumption leads to a spatial econometric reduced form which is somewhat latent and not fully exploited in Aghion and Howitt (1998) or Howitt (2000). Indeed, the global interdependence implied by international R&D spillovers needs to be taken into account in the theoretical model as well as in its empirical counterpart. The empirical specification proposed by Aghion and Howitt (1998) or Howitt (2000) appears then to be misspecified since it omits this interdependence whereas it is fundamental in their theoretical model: their reduced econometric form does not capture all the rich qualitative and quantitative implications of the multi-country Schumpeterian growth model.

The rest of the paper is organized as follows. Section 2 presents the multi-country Schumpeterian growth model. Section 3 introduces our technological diffusion process. Section 4 derives the steady state of per worker income. Section 5 is devoted to the spatial econometric reduced form of the multi-country Schumpeterian growth model and the estimation method we use. Section 6 describes the data set and the interaction or spatial weights matrices used in the estimation. Section 7 presents the econometric results and finally Section 8 concludes.

2 Physical capital accumulation in the multi-country Schumpeterian growth model

2.1 Hypotheses

Production relations Let us consider as a starting point the multi-country Schumpeterian growth model elaborated by Aghion and Howitt (1998) and Howitt (2000). Consider a single country in a world economy with n different countries. There is one final good, produced under perfect competition by labor and a continuum of intermediate products, according to the production function:

$$Y_i(t) = Q_i(t)^{\alpha-1} \int_0^{Q_i(t)} A_i(v,t) x_i(v,t)^{\alpha} L_i(t)^{1-\alpha} dv \tag{1}$$

where $Y_i(t)$ is the country's i gross output at date t, $L_i(t) = L_i(0)e^{n_i t}$ is the flow of raw labor used in production and n_i its rate of growth, $Q_i(t)$ measures the number of different intermediate products produced and used in the country i at date t, $x_i(v,t)$ is the flow output of intermediate product $v \in [0, Q_i(t)]$ used at date t and $A_i(v,t)$ is a productivity parameter attached to the latest version of intermediate product v. As also underlined by Howitt (2000, p.831), in order to underline technology transfer as the main connection between countries, we assume that there is no international trade in goods or factors. Each intermediate product is specific to the country in which it is used and produced, although, as we will see, the idea for how to produce it can originates in other countries.

We assume that labor supply and population size are identical. They both grow exogenously at the fixed proportional rate n_i. The form of the production function, that is the presence of the term $Q_i(t)$ dividing the labor, ensures that growth in product variety does not affect aggregate productivity. Therefore, we suppose as Aghion and Howitt (1998) and Howitt (2000) that the number of products grows as result of serendipitous imitation, not deliberate innovation. Imitation is limited to domestic intermediate products; thus each new product will have the same productivity parameter as a randomly chosen existing product within the country. Each agent has the same propensity to imitate $\xi > 0$, which we assume identical for each country i. Thus the aggregate flow of new products is: $\dot{Q}_i(t) = \xi L_i(t)$. Moreover, since the population growth rate is constant, the number of workers per product $l_i(t) \equiv L_i(t)/Q_i(t)$ converges monotonically to the constant:

$$l_i = n_i/\xi \tag{2}$$

Assume that this convergence has already occurred, so that: $L_i(t) = l_i Q_i(t)$ for all t. The form of the production function (1) ensures that growth in product variety does not affect aggregate productivity. This and the fact that population growth induces product proliferation guarantee that the model does not exhibit the sort of scale effect that Jones (1995) argues is contradicted by postwar trends in R&D spending and productivity.

At symmetric equilibrium, we have: $x_i(t) = \hat{k}_i(t) l_i(t)$ with: $\hat{k}_i(t) \equiv K_i(t)/(A_i(t)L_i(t))$ the capital stock per effective worker, $K_i(t) = \int_0^{Q_i(t)} K_i(v,t)dv$ represents the equality of the total demand and given supply of capital, and $A_i(t) \equiv \frac{1}{Q_i(t)} \int_0^{Q_i(t)} A_i(v,t)dv$ is the average productivity parameter across all sectors. Substitution of $x_i(t)$ at symmetric equilibrium into the production function (1) shows that output per effective worker is given by the familiar intensive-form production function:

$$\hat{y}_i(t) = \hat{k}_i(t)^\alpha \tag{3}$$

with $\hat{y}_i(t) \equiv Y_i(t)/(A_i(t)L_i(t))$ the level of production per effective worker.

The monopolist firms' problem Final output can be used interchangeably as a consumption or capital good, or as an input to R&D sector. Each intermediate product is produced using capital, according to the production function:

$$x_i(v,t) = K_i(v,t)/A_i(v,t) \tag{4}$$

where $K_i(v,t)$ is the input of capital in sector v. Division by $A_i(v,t)$ indicates that successive vintages of the intermediate product are produced by increasingly capital-intensive techniques. Innovations are targeted at specific intermediate products. Each innovation creates an improved version of the existing product, which allows the innovator to replace the incumbent monopolist until the next innovation in that sector. The cost function of the monopolist firm is given by:

$$(r_i(t) + \delta)K_i(v,t) = (r_i(t) + \delta)A_i(v,t)x_i(v,t) \tag{5}$$

where $(r_i(t) + \delta)$ is the cost of the capital, that is the rate of interest $r_i(t)$ and δ is the fixed rate of depreciation. The price schedule, or the inverse demand function $p_i(v,t)$, facing the monopolist is: $p_i(v,t) = \alpha A_i(v,t) x_i(v,t)^{\alpha-1} l_i(t)^{1-\alpha}$. The monopolist firm therefore maximizes the following profit function:

$$\max \pi_i(v,t) = p_i(v,t)x_i(v,t) - (r_i(t) + \delta)A_i(v,t)x_i(v,t) \tag{6}$$

With the properties of the cost and the inverse demand functions, we can resolve the monopolist maximization problem to obtain the equilibrium interest rate:

$$r_i(t) = \alpha^2 \hat{k}_i(t)^{\alpha-1} - \delta \tag{7}$$

Substituting this result in the profit function, we obtain $\pi_i(v,t) = A_i(v,t)\widetilde{\pi}_i l_i(t)$ with $\widetilde{\pi}_i(\hat{k}_i(t)) \equiv \alpha(1-\alpha)\hat{k}_i(t)^\alpha$.

2.2 Vertical innovations

Poisson arrival rate Improvements in the productivity parameters of intermediate products come from R&D activities. This sector uses only the final good as production factor. The Poisson arrival rate of vertical innovations in any sector is:

$$\phi_i(t) = \lambda_i \kappa_i(t)^{\phi} \tag{8}$$

with $0 \leq \phi \leq 1$ the parameter measuring the impact of R&D expenditure on Poisson arrival rate, $\lambda_i > 0$ the parameter indicating the productivity of vertical R&D, $\kappa_i(t) = \frac{S_{i,A}(t)}{Q_i(t)A_i(t)^{max}}$ is the productivity-adjusted expenditure on vertical R&D in each sector.[2] We deflate R&D expenditures in each sector $(S_{i,A}(t)/Q_i(t))$ by $A_i(t)^{max}$ the leading-edge productivity parameter to take into account the force of increasing complexity; as technology advances, the resource cost of further advances increases proportionally. This hypothesis prevents growth from exploding as the amount of capital available as an input to R&D grows without bound. The leading-edge technology is the maximal value of $A_i(v,t)$ at date t defined as:

$$A_i(t)^{max} \equiv \max\{A_i(v,t); v \in [0, Q_i(t)]\} \tag{9}$$

Value of an innovation Define the value of an innovation by $V_i(t)$ and the productivity-adjusted value of an innovation by: $v_i(t) \equiv \frac{V_i(t)}{A_i(t)^{max}}$. The value of an innovation is given by:

$$V_i(t) = \int_t^{\infty} e^{-\int_t^{\tau}(r_i(s)+\phi_i(s))ds}\pi_i(\tau)d\tau \tag{10}$$

Accordingly the value of a vertical innovation at date t is the present value of the future profits to be earned by the incumbent before being replaced by the next innovator in that product. Noting that a firm which innovates at date t has a productivity $A_i(v,\tau) = A_i(t)^{max}$ for all $\tau > t$ until replacement by another which innovates. Introducing equation describing the profit, we can rewrite (10) as follows:

$$v_i(t) = \int_t^{\infty} e^{-\int_t^{\tau}(r_i(s)+\phi_i(s))ds} l_i \widetilde{\pi}_i(\hat{k}_i(\tau))d\tau \tag{11}$$

Deriving with respect to time, we obtain:

$$\frac{\dot{v}_i(t)}{v_i(t)} = r_i(t) + \phi_i(t) - \frac{l_i \widetilde{\pi}_i(\hat{k}_i(t))}{v_i(t)} \tag{12}$$

This equation is the classical research-arbitrage equation. The profit of private firm v in the research sector, denoted by $\pi_{i,A}(v)$, is given by:

$$\pi_{i,A}(v) = \lambda_i \kappa_i(t)^{\phi} \frac{S_{i,A}(v,t)}{S_{i,A}(t)/Q_i(t)} V_i(t) - S_{i,A}(v,t) \tag{13}$$

with $\lambda_i \kappa_i(t)^{\phi}$ the Poisson arrival rate, $S_{i,A}(v,t)$ is the quantity of final good invested in R&D by the firm v, $S_{i,A}(t)/Q_i(t)$ is the quantity of final output invested by all firms in this sector representing here negative externalities due to duplication or overlap

[2] As denoted by Aghion and Howitt (1998), since the prospective payoff is the same in each sector, we divide total R&D expenditures in country i by the number of sectors in this country, so that R&D expenditures are identical in each sector.

research. The marginal cost is supposed equal to one without loss in generalities. The first order condition of profit maximization gives:

$$\frac{d\pi_{i,A}(v)}{dS_{i,A}(v,t)} = 0 \Leftrightarrow 1 = \lambda_i \frac{\kappa_i(t)^{\phi}}{S_{i,A}(t)/Q_i(t)} V_i(t) \tag{14}$$

that is the value of one innovation:

$$v_i(t) = \frac{1}{\lambda_i} \kappa_i(t)^{1-\phi} \tag{15}$$

Taking the derivative with respect to time in both sides and rearranging terms, we obtain the differential equation describing the evolution of the amount of final good invested in R&D sector:

$$\frac{\dot{v}_i(t)}{v_i(t)} = (1-\phi)\frac{\dot{\kappa}_i(t)}{\kappa_i(t)} \Leftrightarrow \frac{\dot{\kappa}_i(t)}{\kappa_i(t)} = \frac{1}{1-\phi}\left[r_i(t) + \lambda_i \kappa_i(t)^{\phi} - \lambda_i \kappa_i(t)^{\phi-1} l_i \widetilde{\pi}_i(\hat{k}_i(t))\right] \tag{16}$$

Growth of the leading-edge parameter Growth in the leading-edge parameter occurs as a result of the knowledge spillovers produced by vertical innovations. Following Caballero and Jaffe (1993), Aghion and Howitt (1998, 1999) and Howitt (1999, 2000) assume that $A_i(t)^{max}$ grows at a rate proportional to the aggregate rate of vertical innovations. The factor of proportionality, which is a measure of the marginal impact of each innovation on the stock of public knowledge, is assumed to equal $\frac{\sigma}{Q_i(t)} > 0$. We divide by $Q_i(t)$ to reflect the fact that as the economy develops an increasing number of specialized products, an innovation of a given size with respect to any given product will have a smaller impact on the aggregate economy. The rate of technological progress equals:

$$g_i(t) \equiv \frac{\dot{A}_i(t)^{max}}{A_i(t)^{max}} = \frac{\sigma}{Q_i(t)} Q_i(t) \lambda_i \kappa_i(t)^{\phi} = \sigma \lambda_i \kappa_i(t)^{\phi} \tag{17}$$

with $\frac{\sigma}{Q_i(t)}$ the factor of proportionality, $Q_i(t)$ is the number of horizontally differentiated goods, $\lambda_i \kappa_i(t)^{\phi}$ is the rate of innovation for each product, $Q_i(t)\lambda_i \kappa_i(t)^{\phi}$ is the aggregate flow of innovation. Therefore, the rate of technological progress equals to the aggregate flow of innovations times the factor of proportionality.

Relation of proportionality between the leading-edge and average parameter Each innovation replaces a randomly chosen $A_i(v,t)$ with the leading-edge technology parameter $A_i(t)^{max}$. Since innovations occur at the rate $\lambda_i \kappa_i(t)^{\phi}$ per product and the average change across innovating sectors is $A_i(t)^{max} - A_i(t)$, we have:

$$\frac{dA_i(t)}{dt} = \lambda_i \kappa_i(t)^{\phi} (A_i(t)^{max} - A_i(t)) \tag{18}$$

As Aghion and Howitt (1998), we can show that the ratio $\frac{A_i(t)^{max}}{A_i(t)}$ converges asymptotically to $1+\sigma$. Thus we assume that $A_i(t)^{max} = A_i(t)(1+\sigma)$ for all t, so that the rate of growth of the average productivity parameter $A_i(t)$ will also given by that of $A_i(t)^{max}$ in equation (17).

2.3 Physical capital accumulation and steady state analysis

The law of motion of aggregate physical capital is given by the fundamental dynamic equation of Solow as in the neoclassical growth model:

$$\dot{\hat{k}}_i(t) = s_{K,i}\hat{k}_i(t)^{\alpha} - (n_i + g_i(t) + \delta)\hat{k}_i(t) \tag{19}$$

where $s_{K,i}$ is the investment rate and δ is the rate of depreciation of physical capital assumed identical for each country.

In this section, we first consider that each economy is independent from others. The evolution of economy i is described by the following system of differential equations:

$$\dot{\hat{k}}_i(t) = s_{K,i}\hat{k}_i(t)^{\alpha} - (n_i + \sigma\lambda_i\kappa_i(t)^{\phi} + \delta)\hat{k}_i(t) \tag{20}$$

$$\dot{\kappa}_i(t) = \frac{\kappa_i(t)}{1-\phi}\left[r_i(t) + \lambda_i\kappa_i(t)^{\phi} - \lambda_i\kappa_i(t)^{\phi-1}l_i\widetilde{\pi}_i(\hat{k}_i(t))\right] \tag{21}$$

with: $g_i(t) = \sigma\lambda_i\kappa_i(t)^{\phi}$.

At steady state, we have $\dot{\hat{k}}_i(t) = \dot{\kappa}_i(t) = 0$ and $g_i^{\star} = \sigma\lambda_i\kappa_i^{\star\phi}$. The equation describing the accumulation of physical capital becomes in implicit form:

$$\hat{k}_i^{\star\alpha} = \frac{s_{K,i}}{n_i + \sigma\lambda_i\kappa_i^{\star\phi} + \delta} \tag{22}$$

We note that an increase of research increases the rate of technological progress at steady state and decreases the ratio capital-output at steady state and therefore the per effective worker physical capital at steady state. We obtain the decreasing curve (K).

For the equation describing the accumulation of R&D, we have at steady state in implicit form the arbitrage equation of the Schumpeterian growth model:

$$1 = \lambda_i\kappa_i^{\star\phi-1}\frac{\widetilde{\pi}_i(\hat{k}_i^{\star})l_i}{r_i^{\star} + \lambda_i\kappa_i^{\star\phi}} \tag{23}$$

We obtain the increasing curve (A). It is increasing since when the per worker physical capital increases, the profit of firms increases and the marginal revenue decreases so that research expenditures need to increase in order to maintain equilibrium in equation (23).

Figure 1 around here

We represent these curves (K) and (A) in the upper right part of Figure 1. It represents the interaction between neoclassical growth model and Schumpeterian growth model of Aghion and Howitt (1992). Indeed, in the lower right part of Figure 1 we represent the neoclassical growth model. The only difference with the well-known graph associated with this model, is the fact that the line $n_i + g_i(t) + \delta$ moves up until the steady state is reached. In fact the effective depreciation rate of capital depends on technology rate of growth which is endogenously determined by research investment. We represent this Schumpeterian part of the model in the upper left part of Figure 1, with the rate of growth of technology which depends on research investments $\kappa_i(t)$. The function is increasing and concave. At steady state, the line representing the effective rate of depreciation is fixed and we can determine all variables at their steady state values.

The classical comparative statics in the Schumpeterian growth literature leads to the following Proposition:

Proposition 1 *The country i's steady state growth rate value ($g_i^\star$) positively depends on its investment rate ($s_{K,i}$) and the productivity of its research sector (λ_i). It depends negatively on the depreciation rate of physical capital (δ).*

Indeed, an increase of the research productivity λ_i makes research more productive which directly induces an increase of the growth rate. However, we can note that *per effective* worker physical capital decreases, since the curve (A) moves up in the upper right part of Figure 1, and the line representing the effective depreciation rate of physical capital moves up too. An increase of the investment rate moves up the curve in the lower right part of Figure 1, and the curve (K) in the upper right part of Figure 1. As we showed, the profit of intermediate firms depends positively on accumulated per effective worker physical capital. Therefore, the devoted resources to the research sector increase and the growth rate increases. In contrast, the accumulated per effective worker physical capital decreases when the depreciation rate of the physical capital increases so that the growth rate decreases.

3 International technological diffusion and the multi-country Schumpeterian growth model

Let us consider now the multi-country Schumpeterian growth model. In order to introduce technological diffusion, we assume that the research productivity parameter λ_i is defined as follows:

$$\lambda_i = \lambda \prod_{j=1}^{n} \left(\frac{A_j(t)}{A_i(t)} \right)^{\gamma_i v_{ij}} \tag{24}$$

We therefore suppose that R&D productivity is a negative function of the technological gap of country i with respect to its *own technological frontier*. This technological frontier is defined as the geometric mean of knowledge levels in all countries denoted by $A_j(t)$, for $j = 1, ..., n$. It is specific to each country because of the v_{ij} parameters, which model the *specific access* of the country i to the accumulated knowledge of all other countries. The general specification proposed in this paper encompasses particular cases generally found in the literature like the world or *global technological leader* (Benhabib and Spiegel, 1994, 2005; or Nelson and Phelps, 1966). We assume that the interaction terms v_{ij} are non negative, finite and non stochastic. We also assume that $\sum_{j=1}^{n} v_{ij} = 1$ for $i = 1, ..., n$ to ensure convergence to parallel growth paths. The parameter $\gamma_i > 1$ measures the absorption capacity of country i which is assumed a function of its human capital stock as: $\gamma_i = \gamma H_i$, with $\gamma < 1$. Introducing equation (24) into the growth rate of the average accumulated knowledge in country i, we have:

$$g_i \equiv \frac{\dot{A}_i(t)}{A_i(t)} = \lambda \sigma \kappa_i(t)^{\phi} \prod_{j=1}^{n} \left(\frac{A_j(t)}{A_i(t)} \right)^{\gamma_i v_{ij}} \tag{25}$$

The idea developed here is very simple. We assume that each country has a technological frontier defined in the last term of equation (25). The gap with respect to this specific technological frontier determines the research productivity of a given country i. Indeed, the farther away a country is from its *own* technological frontier the higher is its productivity in the research sector because it can beneficiate from the accumulated knowledge in other countries. This hypothesis can also be interpreted as international spillovers effect or as spatial externalities (Ertur and Koch, 2007). Therefore, the closer country i is to its *own* technological frontier the more it is difficult to copy foreign technology and the lower is its research productivity λ_i. In contrast, the farther the country i is from its *own* technological frontier the more it beneficiates from foreign technology to innovate and the higher is its research productivity. The distance with respect to countries' *own* technological frontier depends on the resources devoted to the research sector $\kappa_i(t)$. At steady state, all countries have constant rates of growth of their key variables, therefore the gap with respect to their *own* frontier is constant and steady state occurs only if all countries have identical growth rates, or in other words, if all countries converge to parallel long ways of growth. At steady state, we have: $g_i^\star = g_w$ for each country i where g_w is the steady state growth rate or the world growth rate. It is defined as follows:[3]

$$g_w = \lambda \sigma \kappa_i^\phi \prod_{j=1}^{n} \left(\frac{A_j}{A_i} \right)^{\gamma_i v_{ij}} \quad \text{for} \quad i = 1, ..., n \tag{26}$$

Each country has the same steady state growth rate because of the inverse relation between the resources devoted to the research sector and the productivity parameter λ_i. More precisely, a country which has high expenditures in the R&D sector is close to its *own* technological frontier and therefore its research productivity λ_i is low. In contrast, a country, which has low expenditures in the R&D sector is far away from its *own* technology frontier and its research productivity is high. The effect of technology diffusion on research productivity implies convergence to the same growth rate and parallel growth paths at long run.

Although Aghion and Howitt (1998) specify a similar function, they assume that each country has the *same* technological frontier since each country diffuses the *same* quantity of knowledge to all other foreign countries, that is: $v_{ij} = v_j$ for each country. In their model, the technological frontier is therefore *global* and not *local or specific* to each country as we assume. For this reason, as we will show, the interdependence pattern can be embedded into the constant term of their empirical specification, thus preventing full exploitation of some fundamental theoretical and econometric implications of their theoretical model. In our model, we generalize their approach by assuming a richer structure of interdependence between countries. Their model is then just a particular case of ours. Moreover, as we will discuss below, we use the fact that the interaction matrix with general term v_{ij} can be decomposed in order to model North-South R&D diffusion. This allows then for clubs to emerge.

Recall that: $\kappa_i = \frac{S_{A,i}}{Q_i A_i^{max}} = \frac{S_{A,i}}{Y_i} \frac{Y_i}{L_i} \frac{L_i}{Q_i} \frac{1}{(1+\sigma)A_i} = s_{A,i} y_i \frac{n_i}{\xi} \frac{1}{(1+\sigma)A_i}$, where $s_{A,i} = \frac{S_{A,i}}{Y_i}$ is the investment rate in the R&D sector. Defining home technological access as: $v_{ii} \equiv \frac{\gamma_i - 1}{\gamma_i} < 1$, for $i = 1, ..., n$, we have:

$$g_w = \frac{\sigma \lambda}{((1+\sigma)\xi)^\phi} s_{A,i}^\phi y_i^\phi n_i^\phi A_i^{-\phi-1} \prod_{j \neq i}^{n} A_j^{\gamma_i v_{ij}} \tag{27}$$

[3] At this step, all variables are defined at steady state, we therefore drop the time reference.

Taking logarithms of equation (27), we rewrite the obtained equation as:

$$\ln A_i = \frac{1}{1+\phi} \ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}} + \frac{\phi}{1+\phi} \left(\ln s_{i,A} + \ln n_i + \ln y_i\right) + \frac{\gamma H_i}{1+\phi} \sum_{j \neq i}^{n} v_{ij} \ln A_j \tag{28}$$

This equation shows explicitly that the knowledge accumulated in one country depends on the knowledge accumulated in other countries. Our multi-country Schumpeterian growth model implies technological interdependence between countries, therefore each country cannot be analyzed as an independent observation. At this step, assuming that each country diffuses identically, that is $v_{ij} = v_j$ for $j = 1, ..., n$ and $\gamma_i = \gamma$ for $i = 1, ..., n$, Aghion and Howitt (1998) consider the last term of equation (29) as a constant. In contrast, we propose a richer interdependence scheme, rewrite equation (29) in matrix form to obtain:

$$\mathbf{A} = \frac{1}{1+\phi} \ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}} \mathbb{1}_{(\mathbf{n},\mathbf{1})} + \frac{\phi}{1+\phi}(\mathbf{s_A} + \mathbf{y} + \mathbf{n}) + \frac{\gamma}{1+\phi}\mathbf{WA} \tag{29}$$

where $\mathbf{A}$ is the $(n \times 1)$ vector of the logarithms of average technological progress levels, $\mathbb{1}_{(\mathbf{n},\mathbf{1})}$ the $(n \times 1)$ vector of 1, $\mathbf{y}$ the $(n \times 1)$ vector of the logarithms of per worker income levels, $\mathbf{s_A}$ the $(n \times 1)$ vector of the logarithms of the investment rates devoted to the research sector and $\mathbf{n}$ the $(n \times 1)$ vector of the logarithms of working-age population rates of growth. $\mathbf{W}$ is the $(n \times n)$ interaction matrix defined as $\mathbf{W} = \text{diag}[H_i]\mathbf{V}$, where $\text{diag}[H_i]$ is the diagonal matrix of human capital stocks and $\mathbf{V}$ is the matrix collecting the interaction terms v_{ij} for $i \neq j$ given that $v_{ij} = 0$ if $i = j$. Note that, by definition, $\mathbf{W}$ is not row normalized. Note also that, by definition, the elements of $\mathbf{W}$ are nonnegative. We can resolve this equation for $\mathbf{A}$, if $\left(\mathbf{I} - \frac{\gamma}{1+\phi}\mathbf{W}\right)$ is non singular, that is to say if $\frac{\gamma}{1+\phi} \neq 0$ and if $\left|\frac{\gamma}{1+\phi}\right| \leq \frac{1}{\min(l,c)}$ where $l = \max_i \sum_j w_{ij}$ and $c = \max_j \sum_i w_{ij}$:

$$\begin{aligned} \mathbf{A} = & \frac{1}{1+\phi} \left(\mathbf{I} - \frac{\gamma}{1+\phi}\mathbf{W}\right)^{-1} \left(\ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}} \mathbb{1}_{(\mathbf{n},\mathbf{1})}\right) \\ & + \frac{\phi}{1+\phi} \left(\mathbf{I} - \frac{\gamma}{1+\phi}\mathbf{W}\right)^{-1} (\mathbf{s_A} + \mathbf{y} + \mathbf{n}) \end{aligned} \tag{30}$$

This relation shows that the level of average technology depends not only on the R&D expenditures in the home country i but also on the R&D expenditures in foreign countries $j = 1, ..., n$. The impact of foreign R&D expenditures depends on the v_{ij} parameters reflecting interactions between country i and all other countries, and on the human capital stock H_i of the receiving country i reflecting its absorption capacity.

4 Steady state of per worker income

Rewriting the production function in matrix form: $\mathbf{y} = \mathbf{A} + \frac{\alpha}{1-\alpha}\mathbf{S_K}$, where $\mathbf{S_K}$ is the $(n \times 1)$ vector of the logarithms of the investment rates divided by the effective rates of depreciation of physical capital, replacing $\mathbf{A}$ from equation (30) in the production function and rearranging terms, we obtain:

$$\mathbf{y} = \left(\ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}}\right) \mathbb{1}_{(\mathbf{n},\mathbf{1})} + \phi(\mathbf{s_A}+\mathbf{n}) + \frac{\alpha(1+\phi)}{1-\alpha}\mathbf{S_K} - \frac{\alpha\gamma}{1-\alpha}\mathbf{W}\mathbf{S_K} + \gamma\mathbf{W}\mathbf{y} \quad (31)$$

or for a country i:

$$\begin{aligned}\ln y_i = {} & \ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}} + \phi(\ln s_{A,i} + \ln n_i) + \frac{\alpha(1+\phi)}{1-\alpha} \ln \frac{s_{K,i}}{n_i + g_w + \delta} \\ & - \frac{\alpha\gamma H_i}{1-\alpha} \sum_{j\neq i}^{n} v_{ij} \ln \frac{s_{K,j}}{n_j + g_w + \delta} + \gamma H_i \sum_{j\neq i}^{n} v_{ij} \ln y_j \end{aligned} \quad (32)$$

This equation shows that the level of per worker income at steady state depends positively on the same levels in other countries. It is therefore an *implicit* equation. The resolution of this equation for y_i implies rewriting it in an explicit form. We can then study the signs and quantify the effects of each variable on the level of the country i's steady state value of per worker income.[4]

Proposition 2 (Effect of investment rates in physical capital) *The value of per worker income of country i at steady state depends positively on its own investment rate in physical capital ($s_{K,i}$) and positively on the investment rates in physical capital in foreign countries ($s_{K,j}$ for $j = 1, ..., n$ and $j \neq i$). The elasticities of the country i's value of per worker income at steady state with respect to its own investment rate is:*

$$\Xi_i^{s_{K,i}} = \frac{\alpha(1+\phi)}{1-\alpha} + \frac{\alpha\phi}{1-\alpha} \sum_{r=1}^{\infty} \gamma_i^r v_{ii}^{(r)} > 0 \quad (33)$$

and with respect to the investment rate in the country j is:

$$\Xi_i^{s_{K,j}} = \frac{\alpha\phi}{1-\alpha} \sum_{r=1}^{\infty} \gamma_i^r v_{ij}^{(r)} > 0 \quad \text{for} \quad j = 1, ..., n, \quad j \neq i \quad (34)$$

Our multi-country Schumpeterian growth model has the same qualitative predictions as the neoclassical growth model about the effect of investment rates in the physical capital sector. However, because of technological interdependence and the interaction between research expenditures and physical capital accumulation, this model has different quantitative predictions. First, we note that if $\phi = 0$, that is when R&D expenditures have no effect on growth, the elasticities reduce to that of the Solow growth model: $\Xi_i^{s_{K,i}} = \frac{\alpha}{1-\alpha}$ and $\Xi_i^{s_{K,j}} = 0$, for $j = 1, ..., n$. If $\gamma_i = 0$, that is in the absence of technological interdependence, the impact of the investment rate in physical capital is higher than in the Solow growth model: $\frac{\alpha(1+\phi)}{1-\alpha} > \frac{\alpha}{1-\alpha}$. In fact, if the country i has an higher investment rate in physical capital, the profits of intermediate firms increase and the research becomes more attractive. An increase of research expenditures increases the average productivity of the country i and therefore its steady state per worker income value. We note finally that the multi-country Schumpeterian growth model has close quantitative predictions to the Ertur and Koch multi-country Solow model (2007) about the effects of the home and foreign investment rates in physical capital on per worker real income. Indeed, an increase of the investment rate in the

[4] See Appendix 1 for the proof.

home country i or in the foreign country j, $s_{K,j}$ for $j = 1, ..., n$, increases the per worker income of the country i because of the multiplier effect implied by technological interdependence. These effects are higher than in the case of the absence of technological diffusion. Indeed, when a foreign country increases its average level of technology as described previously and because of technological interdependence, it increases first the productivity of R&D of country i, second the average technology in country i and finally the level of per worker income in country i. The direct impact of the investment rate $s_{K,i}$ is higher because of the multiplier effect implied by technological interdependence. We note finally that all these elasticities are all specific to each country because of differences in their interaction schemes subsumed in the $\mathbf{W}$ matrix.

Proposition 3 (Effect of working-age population growth rates) *The country i's value of per worker income at steady state depends positively on the working-age population growth rates in foreign countries (n_j for $j = 1, ..., n$ and $j \neq i$). However, an increase of the working-age population growth rates in the home country i has an ambiguous effect on relative productivity because, although it has a positive direct effect on the R&D function, it has also a negative effect as it reduces per worker physical capital through the standard neoclassical mechanism of dilution. The elasticities of the country i's value of per worker income at steady state with respect to its own working-age population growth rate is:*

$$\Xi_i^{n_i} = -\frac{\alpha}{1-\alpha}\left(\frac{n_i}{n_i + g_w + \delta}\right) + \frac{\alpha\phi}{1-\alpha}\left(\frac{g_w + \delta}{n_i + g_w + \delta}\right)\left(1 + \sum_{r=1}^{\infty} \gamma_i^r v_{ii}^{(r)}\right) \tag{35}$$

and with respect to the working-age population growth rate in the country j is:

$$\Xi_i^{n_j} = \frac{\alpha\phi}{1-\alpha}\left(\frac{g_w + \delta}{n_j + g_w + \delta}\right)\sum_{r=1}^{\infty} \gamma_i^r v_{ij}^{(r)} > 0 \quad for \quad j = 1, ..., n, \quad j \neq i \tag{36}$$

As previously, we note that if $\phi = 0$, that is when R&D expenditures have no effect on growth, the elasticities reduces to that of the Solow growth model: $\Xi_i^{n_i} = -\frac{\alpha}{1-\alpha}\left(\frac{n_i}{n_i+g_w+\delta}\right)$ and $\Xi_i^{n_j} = 0$, for $j = 1, ..., n$ and $j \neq i$.

The impact of own elasticity is positive if: $\phi \frac{g_w+\delta}{n_i}\left(1 + \sum_{r=1}^{\infty} \gamma_i^r v_{ii}^{(r)}\right) > 1$. Therefore, the effect of home working-age population growth rate is positive if the impact of R&D expenditures (ϕ) is high enough, which is coherent with economic intuition since working-age population growth rate has a positive impact on horizontal innovation. The higher a country's working-age population growth rate (n_i) is, the higher is the possibility to have a negative effect. Moreover, when the depreciation rate of physical capital δ or the world growth rate g_w are high it is possible to have a positive impact. Finally, because of technological interdependence, the possibility to have a positive impact of working-age population growth rate is higher if γ_i is high or if country i beneficiates more from foreign technology throughout v_{ij} parameters and human capital H_i.

Proposition 4 (Effect of research expenditures) *The country i's value of per worker income at steady state depends positively on its own research expenditures ($s_{A,i}$) and positively on the research expenditures in foreign countries ($s_{A,j}$ for $j = 1, ..., n$*

and $j \neq i$). The elasticities of the country i's value of per worker income at steady state with respect to its own research expenditures is:

$$\Xi_i^{s_{A,i}} = \phi + \phi \sum_{r=1}^{\infty} \gamma_i^r v_{ii}^{(r)} > 0 \tag{37}$$

and with respect to research expenditures in the country j is:

$$\Xi_i^{s_{A,j}} = \phi \sum_{r=1}^{\infty} \gamma_i^r v_{ij}^{(r)} > 0 \tag{38}$$

The impact of research expenditures in home or foreign countries on per worker income at steady state is positive. We first note that, because of technological interdependence we have an international R&D diffusion process, which is consistant with the empirical results implied by the Coe and Helpman (1995) model and subsequent studies. Another effect is underlined by these authors: the effect of home R&D expenditures are higher when we take into account foreign R&D expenditures. Indeed, the impact of the elasticity of R&D expenditures is higher when $\gamma_i \neq 0$. Therefore, our multi-country Schumpeterian growth model seems consistent with these empirical results. We quantify the implied international R&D diffusion effect in Section 7.

5 Econometric specifications and estimation method

Using equation (32), we obtain the following econometric reduced form of the multi-country Schumpeterian growth model, describing the per worker real income at steady state, at a given time:

$$\begin{aligned}\ln y_i = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \beta_2 \ln s_{A,i} + \beta_3 \ln n_i + \theta H_i \sum_{j \neq i}^{n} v_{ij} \ln \frac{s_{K,j}}{n_j + 0.05} \\ + \gamma H_i \sum_{j \neq i}^{n} v_{ij} \ln y_j + \varepsilon_i\end{aligned} \tag{39}$$

with: β_0, the constant identical for each country, $\beta_1 = \frac{\alpha(1+\phi)}{1-\alpha} > 0$ the coefficient associated with the investment rate in physical capital divided by the effective depreciation rate of the home country i, $\beta_2 = \beta_3 = \phi > 0$ the coefficients associated with the investment rate in the R&D sector and the working-age population growth rate respectively, $\theta = -\frac{\alpha\gamma}{1-\alpha} < 0$ the coefficient associated with the investment rate in physical capital divided by the effective depreciation rate of the foreign country j, for $j = 1, ..., n$, $j \neq i$, and $\gamma > 0$ the spatial autocorrelation coefficient.

Finally, the error terms, simply added to equation (32) to get the estimable econometric specification, ε_i, for $i = 1, ..., n$, are assumed identically and independently distributed.[5] In matrix form, we obtain a particular constrained version of the well known

[5] Ideally the error term should be introduced in the theoretical development as uncertainty and unobserved structural shocks, but this is beyond the scope of the present paper.

specification in the spatial econometric literature refered to as the Spatial Durbin Model (SDM):[6]

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \theta\mathbf{W}\mathbf{Z} + \gamma\mathbf{W}\mathbf{y} + \boldsymbol{\varepsilon} \tag{40}$$

where $\mathbf{y}$ is the $(n \times 1)$ vector of per worker income levels; $\mathbf{X}$ is the $(n \times 4)$ matrix of the exogenous variables: the constant, the logarithms of the investment rates in physical capital divided by the effective depreciation rates, the logarithms of working-age population growth rates and the logarithms of expenditures in the research sector; $\mathbf{W}$ is the $(n \times n)$ interaction matrix or the so called spatial weights matrix. $\mathbf{WZ}$ is the $(n \times 1)$ vector of the spatial lag of the logarithms of the investment rates in physical capital divided by the effective depreciation rates and $\mathbf{Wy}$ is the so called endogenous spatial lag variable. θ is a scalar parameter, $\boldsymbol{\beta}$ is a (4×1) parameters vector and γ is the spatial autocorrelation parameter. $\boldsymbol{\varepsilon}$ is the $(n \times 1)$ vector of error terms assumed identically and independently distributed with mean zero and variance $\sigma^2\mathbf{I_n}$.

In the spatial econometric literature, the spatial weights matrix $\mathbf{W}$ is most of the time row normalized. One can then easily prove, using the Gershgorin's theorem, that the inverse matrix $(\mathbf{I} - \gamma\mathbf{W})^{-1}$ exists if $|\gamma| < 1$. For a non row normalized $\mathbf{W}$ matrix such as the one we consider, the case is less obvious as in general $(\mathbf{I} - \gamma\mathbf{W})$ will be singular for certain values of $|\gamma| < 1$. However one can nevertheless show that $(\mathbf{I} - \boldsymbol{\gamma}\mathbf{W})$ is non singular if $|\gamma| < \frac{1}{\min(l,c)}$ where $l = \max_i \sum_j w_{ij}$ and $c = \max_j \sum_i w_{ij}$. Note also that a model which has a spatial weights matrix which is not row normalized can always be normalized in such a way that the inverse needed to solve the model will exist in an easily established parameter space. Indeed, rewriting equation (43) with a non row normalized $\mathbf{W}$ as follows:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \theta^*\mathbf{W^*Z} + \gamma^*\mathbf{W^*y} + \boldsymbol{\varepsilon} \tag{41}$$

where $\theta^* = \theta a$, $\gamma^* = \gamma a$, $\mathbf{W^*} = \frac{1}{a}\mathbf{W}$ and $a = \min(l,c)$, it can be easily seen that $|\mathbf{I} - \gamma^*\mathbf{W}^*| \neq 0$ and therefore that the inverse exists for:

$$|\gamma^*| < \frac{1}{\min\left(\frac{l}{a}, \frac{c}{a}\right)} = \frac{1}{\frac{1}{a}\min(l,c)} = 1 \tag{42}$$

One could then estimate θ^* and γ^* as parameters and since $\theta^* = \theta a$ and $\gamma^* = \gamma a$, one could estimate θ as $\frac{\theta^*}{a}$ and γ as $\frac{\gamma^*}{a}$. [7]

For ease of exposition, equation (40) may also be written as a Spatial Autoregressive Model (SAR) as follows:

$$\mathbf{y} = \widetilde{\mathbf{X}}\mathbf{b} + \gamma\mathbf{W}\mathbf{y} + \boldsymbol{\varepsilon} \tag{43}$$

with $\widetilde{\mathbf{X}} = [\mathbf{X} \quad \mathbf{WZ}]$ and $\mathbf{b} = (\boldsymbol{\beta}', \boldsymbol{\theta})'$. We can therefore write the reduced form of the SAR model as follows:

$$\mathbf{y} = (\mathbf{I} - \boldsymbol{\gamma}\mathbf{W})^{-\mathbf{1}}\widetilde{\mathbf{X}}\mathbf{b} + (\mathbf{I} - \boldsymbol{\gamma}\mathbf{W})^{-\mathbf{1}}\boldsymbol{\varepsilon} \tag{44}$$

[6] In the spatial econometrics literature, this kind of econometric specification, including the spatial lags of all the exogenous variables in addition to the spatial lag of the endogenous variable, is referred to as the Spatial Durbin Model (SDM): $\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{WX}\boldsymbol{\theta} + \gamma\mathbf{Wy} + \boldsymbol{\varepsilon}$. The model with the endogenous spatial lag variable and the explanatory variables only is referred to as the mixed regressive, Spatial Autoregressive Model (SAR): $\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \gamma\mathbf{Wy} + \boldsymbol{\varepsilon}$ (see Anselin, 1988; Anselin and Bera, 1998; or Anselin, 2006).

[7] To keep the notations as simple as possible, we omit the stars in the remaining of the paper.

If γ is less than the reciprocal of the largest eigenvalue of $\mathbf{W}$ in absolute value, the inverse matrix in equation (44) can be expanded into an infinite series as:

$$(\mathbf{I}-\gamma\mathbf{W})^{-1}=\mathbf{I}+\gamma\mathbf{W}+\gamma^2\mathbf{W^2}+...+\gamma^r\mathbf{W^r}+...=\sum_{r=0}^{\infty}\gamma^r\mathbf{W^r} \tag{45}$$

The reduced form has two important implications. First, in conditional mean, real income per worker in a location i will not only be affected by the logarithms of the investment rates in physical capital divided by the effective depreciation rates, the logarithms of working-age population growth rates and the logarithms of expenditures in the research sector in location i, but also by those in all other locations through the inverse spatial transformation $(\mathbf{I}-\gamma\mathbf{W})^{-1}$. This is the so-called spatial multiplier effect or global interaction effect, which is interpreted here as a technological multiplier effect. Second, a random shock in a specific location i does not only affect the real income per worker in i, but also has an impact on the real income per worker in all other locations through the same inverse spatial transformation. This is the so-called spatial diffusion process of random shocks.

The variance-covariance matrix for $\mathbf{y}$ is easily seen to be equal to:

$$V(\mathbf{y})=\sigma^2\mathbf{(I-\gamma W)^{-1}(I-\gamma W')^{-1}} \tag{46}$$

The structure of this variance-covariance matrix is such that every location is correlated with every other location in the system, but closer location more so. It is also interesting to note that the diagonal elements in equation (46), the variance at each location, are related to the neighborhood structure and therefore are not constant, leading to heteroskedasticity even though the initial process is not heteroskedastic.

It also follows from the reduced form (44) that the spatially lagged variable $\mathbf{Wy}$ is correlated with the error term since:

$$E(\mathbf{Wy\varepsilon'})=\sigma^2\mathbf{W(I-\gamma W)^{-1}}\neq 0 \tag{47}$$

Therefore OLS estimators will be biased and inconsistent. The simultaneity embedded in the $\mathbf{Wy}$ term must be explicitly accounted for in a maximum likelihood estimation framework as first outlined by Ord (1975).[8] More recently, Lee (2004) presents a comprehensive investigation of the asymptotic properties of the maximum likelihood estimators of SAR models.

Under the hypothesis of normality of the error term, the log-likelihood function for the SAR model (43) is given by:

$$\begin{aligned}\ln L(\mathbf{b}',\gamma,\sigma^2)=&-\frac{n}{2}\ln(2\pi)-\frac{n}{2}\ln(\sigma^2)+\mathbf{ln\,|I-\gamma W|}\\&-\frac{1}{2\sigma^2}\left[\mathbf{(I-\gamma W)y-\widetilde{X}b}\right]'\left[\mathbf{(I-\gamma W)y-\widetilde{X}b}\right]\end{aligned} \tag{48}$$

An important aspect of this log-likelihood function is the Jacobian of the transformation, which is the determinant of the $(n\times n)$ full matrix $\mathbf{(I-\gamma W)}$ for our model. This could complicate the computation of the maximum likelihood estimators which involves the repeated evaluation of this determinant. However Ord (1975) suggested

[8] In addition to the maximum likelihood method, the method of instrumental variables (Anselin 1988, Kelejian and Prucha 1998, Lee 2003) may also be applied to estimate SAR models (see Anselin, 2006, for a technical review).

that it can be expressed as a function of the eigenvalues ω_i of the spatial weights matrix as:

$$|\mathbf{I} - \gamma\mathbf{W}| = \prod_{i=1}^{n}(1 - \gamma\omega_i) \quad \Longrightarrow \quad \ln|\mathbf{I} - \gamma\mathbf{W}| = \sum_{i=1}^{n}\ln(1 - \gamma\omega_i) \tag{49}$$

This expression simplifies considerably the computations since the eigenvalues of $\mathbf{W}$ only have to be computed once at the outset of the numerical optimization procedure.

From the usual first-order conditions, the maximum likelihood estimators of $\mathbf{b}$ and σ^2, given γ, are obtained as:

$$\hat{\mathbf{b}}_{ML}(\gamma) = (\widetilde{\mathbf{X}}'\widetilde{\mathbf{X}})^{-1}\widetilde{\mathbf{X}}'(\mathbf{I} - \gamma\mathbf{W})\mathbf{y} \tag{50}$$

$$\hat{\sigma}^2_{ML}(\gamma) = \frac{1}{n}\left[(\mathbf{I} - \gamma\mathbf{W})\mathbf{y} - \widetilde{\mathbf{X}}\hat{\mathbf{b}}_{ML}(\gamma)\right]'\left[(\mathbf{I} - \gamma\mathbf{W})\mathbf{y} - \widetilde{\mathbf{X}}\hat{\mathbf{b}}_{ML}(\gamma)\right] \tag{51}$$

Note that, for convenience:

$$\hat{\mathbf{b}}_{ML}(\gamma) = \hat{\mathbf{b}}_O - \gamma\hat{\mathbf{b}}_L \tag{52}$$

where $\hat{\mathbf{b}}_O = (\widetilde{\mathbf{X}}'\widetilde{\mathbf{X}})^{-1}\widetilde{\mathbf{X}}'\mathbf{y}$ and $\hat{\mathbf{b}}_L = (\widetilde{\mathbf{X}}'\widetilde{\mathbf{X}})^{-1}\widetilde{\mathbf{X}}'\mathbf{W}\mathbf{y}$. Define $\hat{\mathbf{e}}_O = \mathbf{y} - \widetilde{\mathbf{X}}\hat{\boldsymbol{\beta}}_O$ and $\hat{\mathbf{e}}_L = \mathbf{y} - \widetilde{\mathbf{X}}\hat{\boldsymbol{\beta}}_L$, it can be then easily seen that:

$$\hat{\sigma}^2_{ML}(\gamma) = \left[\frac{(\hat{\mathbf{e}}_O - \gamma\hat{\mathbf{e}}_L)'(\hat{\mathbf{e}}_O - \gamma\hat{\mathbf{e}}_L)}{n}\right] \tag{53}$$

Substitution of (50) and (51) in the log-likelihood function (48) yields a concentrated log-likelihood as a non-linear function of a single parameter γ:

$$\begin{aligned}\ln L(\gamma) = &-\frac{n}{2}\left[\ln(2\pi) + 1\right] + \sum_{i=1}^{n}\ln(1 - \gamma\omega_i) \\ &-\frac{n}{2}\ln\left[\frac{(\hat{\mathbf{e}}_O - \gamma\hat{\mathbf{e}}_L)'(\hat{\mathbf{e}}_O - \gamma\hat{\mathbf{e}}_L)}{N}\right]\end{aligned} \tag{54}$$

where $\hat{\mathbf{e}}_O$ and $\hat{\mathbf{e}}_L$ are the estimated residuals in a regression of $\mathbf{y}$ on $\mathbf{X}$ and $\mathbf{W}\mathbf{y}$ on $\mathbf{X}$, respectively. A maximum likelihood estimate for γ is obtained from a numerical optimization of the concentrated log-likelihood function (34).[9] Under the regularity conditions described for instance in Lee (2004), it can be shown that the maximum likelihood estimators have the usual asymptotic properties, including consistency, normality, and asymptotic efficiency.[10]

The asymptotic variance-covariance matrix follows as the inverse of the information matrix, defining $\mathbf{W_A} = \mathbf{W}(\mathbf{I} - \gamma\mathbf{W})^{-1}$ to simplify notation, we have:

AsyVar$[\mathbf{b}', \gamma, \sigma^2] =$

$$\begin{bmatrix} \frac{1}{\sigma^2}\widetilde{\mathbf{X}}'\widetilde{\mathbf{X}} & \frac{1}{\sigma^2}(\widetilde{\mathbf{X}}'\mathbf{W_A}\tilde{\mathbf{X}}\mathbf{b})' & 0 \\ \frac{1}{\sigma^2}\widetilde{\mathbf{X}}'\mathbf{W_A}\tilde{\mathbf{X}}\mathbf{b} & tr\left[(\mathbf{W_A} + \mathbf{W_A}')\mathbf{W_A}\right] + \frac{1}{\sigma^2}(\mathbf{W_A}\widetilde{\mathbf{X}}\mathbf{b})'(\mathbf{W_A}\widetilde{\mathbf{X}}\mathbf{b}) & \frac{1}{\sigma^2}tr\mathbf{W_A} \\ 0 & \frac{1}{\sigma^2}tr\mathbf{W_A} & \frac{n}{2\sigma^4} \end{bmatrix}^{-1}$$

[9] The reader unfamiliar with spatial econometrics methods can refer to LeSage (1999) (http://www.rri.wvu.edu/WebBook/LeSage/etoolbox/index.html) who also provides Matlab routines for estimating such models in his Econometrics Toolbox (http://www.spatial-econometrics.com).

[10] The quasi-maximum likelihood estimators of the SAR model can also be considered if the disturbance in the model are not truly normally distributed (Lee 2004).

$$(55)$$

Since equation (39) is a model including both the Schumpeterian growth model of Aghion and Howitt (1992) and the neoclassical Solow growth model, it is possible to test explicitly the impact of R&D on growth at long run. In fact, if $\phi = 0$, or in other words, if R&D does not influence the Poisson arrival rate of new knowledge, the model reduces to the Solow growth model with technological interdependence (see also Ertur and Koch, 2007) since knowledge increases only with exogenous technological progress. In fact, $\phi = 0$ implies $\beta_2 = 0$ and $\beta_3 = 0$ in equation (39), we therefore obtain the following econometric reduced form:

$$\ln y_i = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \theta H_i \sum_{j \neq i}^{n} v_{ij} \ln \frac{s_{K,j}}{n_j + 0.05} + \gamma H_i \sum_{j \neq i}^{n} v_{ij} \ln y_j + \varepsilon_i \quad (56)$$

with: β_0 the identical constant for each country; $\beta_1 = \frac{\alpha}{1-\alpha} > 0$ the coefficient associated with the investment rates in physical capital divided by the effective depreciation rate of the home country i; $\theta = -\frac{\alpha\gamma}{1-\alpha} < 0$ the coefficient associated with the investment rates in physical capital divided by the effective depreciation rate of the foreign country j, for $j = 1, ..., n$, and $\gamma > 0$ the spatial autocorrelation coefficient. Finally, the error terms ε_i, for $i = 1, ..., n$, are assumed normally, identically and independently distributed. We therefore have, in addition to the preceding linear constraints, the following non linear constraint: $\beta_1 \gamma = -\theta$. In matrix form, we have:

$$\mathbf{y} = \underline{\mathbf{X}}\underline{\boldsymbol{\beta}} - \mathbf{W}\mathbf{Z}\beta_1\gamma + \boldsymbol{\gamma}\mathbf{W}\mathbf{y} + \boldsymbol{\varepsilon} \quad (57)$$

with $\underline{\mathbf{X}} = [\boldsymbol{\iota} \quad \mathbf{Z}]$, where $\boldsymbol{\iota}$ is the $(n \times 1)$ unit vector and $\underline{\boldsymbol{\beta}} = (\beta_0,\ \beta_1)'$. Equation (57) is a constrained form of the Spatial Durbin Model (SDM) (40) which can be easily shown to be equivalent to the following Spatial Error Model (SEM), in matrix form:

$$\begin{aligned} \mathbf{y} &= \underline{\mathbf{X}}\underline{\boldsymbol{\beta}} + \varepsilon_{\mathbf{Solow}} \\ \varepsilon_{\mathbf{Solow}} &= \gamma \mathbf{W} \varepsilon_{\mathbf{Solow}} + \boldsymbol{\varepsilon} \end{aligned} \quad (58)$$

Using the previous set of constraints, it is therefore possible to test endogenous technological progress implied by the Schumpeterian growth model against neoclassical exogenous technological progress. In other words, in our new integrated theoretical and methodological framework characterized by technological interactions, we can build a straightforward econometric test of the multi-country Solow growth model against the multi-country Schumpeterian growth model. To the best of our knowledge, this question has not been resolved until now in the growth literature.

Finally, if we constrain the coefficient α to some appropriate value (we take one third), we obtain the following econometric reduced form:

$$\ln TFP_i = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \beta_2 \ln s_{A,i} + \beta_3 \ln n_i + \gamma H_i \sum_{j \neq i}^{n} v_{ij} \ln TFP_j + \varepsilon_i \quad (59)$$

where: $\ln TFP_i = \ln y_i - 0.5 \ln \frac{s_{K,i}}{n_i + 0.05}$ is the Total Factor Productivity of country i at steady state; $\beta_1 = \beta_2 = \beta_3 = \phi$ are the coefficients associated with the investment rate divided by the effective depreciation rate, the coefficient associated with the investment rate in the research sector and the working-age population growth rate respectively.

γ is the spatial autocorrelation parameter. In matrix form, the unrestricted model is written as follows:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \gamma\mathbf{W}\mathbf{y} + \boldsymbol{\varepsilon} \tag{60}$$

We therefore obtain a Spatial Autoregressive Model (SAR) where Total Factor Productivity of one country depends on Total Factor Productivity in other countries. It is therefore possible to construct explicitly the constrained model and identify ϕ and γ.

The model implies that the R&D of one country spills over countries. In fact, the multi-country Schumpeterian growth model has also a quantitative prediction about the impact of international R&D diffusion on Total Factor Productivity (and on the level of per worker income at steady state). It is possible to quantify the effect of the R&D level of one country on its own Total Factor Productivity but also on the Total Factor Productivity of other countries. Indeed, we can evaluate the elasticity of the Total Factor Productivity of the home country i with respect to its own and to foreign R&D expenditures and show that they are also given by equations (37) and (38). We therefore obtain the estimated matrix of elasticities, using the coefficients of the econometric reduced form:

$$\widehat{\boldsymbol{\Xi}}^{\mathbf{sA}}_{\mathbf{TFP}} = \hat{\beta}_2 \left(\mathbf{I} - \hat{\gamma}\mathbf{W}\right)^{-1} \tag{61}$$

and the Delta method can then be used to assess statistical significance of these elasticities under the regularity conditions described by Lee (2004).

6 Data and spatial weights matrices

We extract our basic data from the Heston *et al.* (2006) Penn World Tables (PWT version 6.2), which contain information on real income, investment and population (among many other variables) for a large number of countries. We use data from the World Investment Report (2005) of the United Nations Conference on Trade and Development (UNCTD) for R&D expenditures. We use a sample of 59 countries over the period 1990-2003. The sample contains 7 African countries, 21 North and South American countries, 9 Asian countries, 20 European countries and 2 Oceanic countries (see Table 3 for a complete list of countries).

We measure n_i, for $i = 1, ..., n$, as the average growth of the working-age population (ages 15 to 64). For this, we have computed the number of workers as: $RGDPCH \times POP/RGDPW$, where $RGDPCH$ is real GDP per capita computed by the chain method, $RGDPW$ is real-chain GDP per worker, and POP is the total population. Real income per worker is measured by the real GDP computed by the chain method, divided by the number of workers. The saving rate $s_{K,i}$, for $i = 1, ..., n$, is measured as the average share of gross investment in GDP over the period as in Mankiw *et al.* (1992). The variable $s_{A,i}$, is measured as the average share gross domestic expenditure on R&D (GERD) relative to GDP over the 1991-2001 period. Finally, like Mankiw *et al.* (1992) among others, we use $g_w + \delta = 0.05$.

As already mentioned, the interaction matrix $\mathbf{W}$ corresponds to the so-called spatial weights matrix commonly used in spatial econometrics to model spatial interdependence between observations (Anselin 2006; Anselin and Bera, 1998). Unlike the time series case, there is no unique natural ordering of cross section observations in space and the spatial weights matrix is the fundamental tool to impose a “relevant” order structure by specifying “neighborhood sets” for each observation. More precisely, each country is connected to a set of neighboring countries by means of an *exogenous* pattern introduced in $\mathbf{W}$. By convention an observation is not a neighbor to itself so that elements on the main diagonal are set to zero $w_{ii} = 0$, whereas in each row i, a non zero element w_{ij} defines j as being a neighbor of i and further specifies the way i is connected to j.

Many different spatial weights matrices may then be specified to study the same issue and it may be difficult to identify the most "relevant" matrix, leaving the room for some arbitrariness. Sensitivity analysis of the results plays then an important role in practice. Traditionally, connectivity has been understood as geographical proximity, various weights matrices based on geographical space have therefore been used in the spatial econometric literature such as contiguity, nearest neighbors and geographical distance based matrices. However the definition is in fact much broader and can be generalized to any network structure to reflect any kind of interactions between observations. As also underlined by Durlauf et al. (2005, p. 643-645), what really matters when adapting these methods to growth econometrics is the identification of the appropriate notion of space and of the appropriate similarity or interaction measure. By analogy to Akerlof (1997) countries may be considered as localized in some general socio-economic and institutional or political space defined by a range of factors. Implementation of spatial methods requires then to identify accurately their localisation in such a general space. Ideally, such a matrix should be theory based but this is beyond the scope of the present paper.

We adopt here a heuristic approach by specifying two different interaction matrices in order to relate our results to those obtained in the empirical literature. We thus assume that technological interactions are function of the capacity of absorption of new technology measured by the human capital stock of the receiving country as implied by our model and of some *ad hoc* measure of similarity between countries.[11]

As traditionally done in the spatial econometric literature, we therefore design our first interaction matrix $\mathbf{W1}$ using a decreasing function of pure geographical distance, more precisely great-circle distance between country capitals. Geographical distance has also been considered among others by Eaton and Kortum (1996), Ertur and Koch (2007) and Moreno and Trehan (1997). Moreover, Klenow and Rodriguez-Clare (2005, p. 28-29) suggest that use of pure geographical distance could capture trade and FDI related spillovers. Keller (2002) finds evidence that international diffusion of technology is geographically localized, in the sense that the productivity effects of R&D decline with the geographical distance between countries. The functional form we consider is simply the negative exponential of distance as also suggested by Keller (2002) among others. The general term of this matrix $\mathbf{W1}$, designed to capture technological interactions, is defined as $w1_{ij} = H_i v1_{ij}$ where:

$$v1_{ij} = \begin{cases} 0 \text{ if } \quad i = j \\ e^{-d_{ij}} / \sum_{j \neq i} e^{-d_{ij}} \quad \text{otherwise} \end{cases} \tag{62}$$

with d_{ij} is the great-circle distance between country capitals and H_i the human capital stock of the receiving country i. We do not mean here that geographic distance matters *per se* in growth theory. We rather use it as a crude proxy for socio-economic or institutional proximity. Furthermore, its exogeneity is largely admitted and therefore represents its main advantage. Note that this matrix differs substantially from the

[11] ***A detailed discussion of some potential interaction patterns that are usefully incorporated in the spatial weight matrix is presented in Appendix 2.***

one used by Ertur and Koch (2007) as it includes human capital stocks to reflect the capacity of absorption of new technology and is therefore partially theory based.

The second interaction matrix we consider, **W2**, is a matrix based on trade flows. Grossman and Helpman (1991), Coe and Helpman (1995) and Coe *et al.* (1997) among others, suggest that international trade may be considered as a major diffusion vector of technological progress so that, in our framework, trade flows may proxy multi-country technological interactions.[12] The general term of this matrix **W2** is defined as $w2_{ij} = H_i v2_{ij}$ where:

$$v2_{ij} = \begin{cases} 0 \text{ if } \quad i = j \\ m_{ij} / \sum_{j \neq i} m_{ij} \quad \text{otherwise} \end{cases} \tag{63}$$

where m_{ij} is defined as the average imports of country i coming from country j over the 1990-2000 period to prevent endogeneity problems that might arise. Like the previous one, this matrix is also partially theory based as it includes human capital stocks. We use data provided by Feenstra and Lipsey available at: `http://cid.econ.ucdavis.edu/` on world bilateral trade. In order to capture intra-OECD spillovers as Coe and Helpman (1995), North-South spillovers as Coe *et al.* (1997) and both direct and indirect international spillovers as also proposed by Lumenga-Neso *et al.* (2005), we consider the bloc-triangular structure as discussed below.

Finally, we measure human capital stock with the Mincerian equation also used by Hall and Jones (1999) or Caselli (2005). For this, we use the new database developed recently by Cohen and Soto (2007), which uses the information on educational attainment by age. This information has not been exploited before. To achieve this, Cohen and Soto (2007) use the following sources: the OECD database on education; national censuses or surveys published by UNESCOs Statistical Yearbook and the Statistics of educational attainment and illiteracy and censuses obtained directly from national statistical agencies web pages.[13]

7 Econometric results

The Solow growth model Derive first the econometric specification from the textbook Solow growth model as proposed by Mankiw *et al.* (1992) since it constitutes a particular case of the multi-country Schumpeterian growth model when R&D expenditures have no effect on growth and development ($\phi = 0$) and when there is no technological interdependence between countries ($\gamma = 0$). We have, for country i:

$$\ln y_i = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \varepsilon_{Solow,i} \tag{64}$$

In matrix form, we have:

$$\mathbf{y} = \underline{\mathbf{X}\boldsymbol{\beta}} + \varepsilon_{\mathbf{Solow}} \tag{65}$$

In the first column of Table 1, we estimate the textbook Solow model using the heteroscedasticity consistent covariance matrix estimator of White (1980) in the Ordinary

[12] Note that our purpose here is not to artificially include trade in our growth model, where we assumed no international trade in goods and factors, but instead to define an alternative measure of technological interactions. Structural integration of trade is clearly beyond the scope of the present paper.

[13] Data on human capital are publicly available at `http://www.iae-csic.uab.es/soto/data.htm`.

Least Squares estimation. Our results for its qualitative predictions are essentially identical to those of Mankiw *et al.* (1992), since the coefficient associated to the investment rate divided by the working-age population growth rate has the predicted sign and is significant.

Table 1 around here

The econometric specification of Aghion and Howitt (1998) and Howitt (2000) Derive now the econometric specification of the multi-country Schumpeterian growth model as proposed by Aghion and Howitt (1998) or Howitt (2000). They assume that $w_{ij} = w_j$ so that each country diffuses the same amount of knowledge to other countries. Therefore, they consider that the last term of equation (32), can be incorporated in the constant term since it is identical for each country. In other words, the technological frontier is viewed as identical for each country. Writing the restricted version of equation (39) under their hypothesis, which amounts to omit the spatial lags of the endogenous and the exogenous variables, we have:

$$\ln y_i = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \beta_2 \ln s_{A,i} + \beta_3 \ln n_i + \varepsilon_{AH,i} \tag{66}$$

where β_0 is a constant, identical for all countries; $\beta_1 = \frac{\alpha(1+\phi)}{1-\alpha} > 0$ is the coefficient associated to the investment rate divided by the effective depreciation rate of the accumulated physical capital and $\beta_2 = \beta_3 = \phi > 0$ is the coefficient associated with the R&D expenditures. Finally, the error terms $\varepsilon_{AH,i}$ for $i = 1, ..., n$, are assumed identically and independently distributed. The econometric specification proposed by Aghion and Howitt (1998) or Howitt (2000), therefore behaves empirically as if $\gamma = 0$, i.e. as if there is no technological interdependence. In matrix form, we have:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}_{\mathbf{AH}} \tag{67}$$

In column 2 of Table 1, we first estimate the unrestricted version of the econometric reduced form proposed by Aghion and Howitt (1998) and Howitt (2000) using the heteroscedasticity consistent covariance matrix estimator of White (1980) in the Ordinary Least Squares estimation. Our result shows that R&D expenditures have a positive and significant impact on the level of per worker income at steady state as expected. Moreover, the coefficient of the investment rate divided by the working-age population growth rate is also significant. However the coefficient associated with the working-age population growth rate, reflecting the effect of horizontal differentiation, is not significant. Estimation of the model, which includes the theoretical restrictions $\beta_2 = \beta_3 = \phi$ yields similar results.

The multi-country Schumpeterian growth model v.s. the multi-country Solow growth model The Solow growth model and the Aghion and Howitt (1998) or Howitt (2000) models are particular cases of our integrated multi-country Schumpeterian growth model. In fact the Solow growth model omits R&D expenditures variables and technological interdependence implying biased estimation. Using straightforward algebra, we can indeed rewrite the error term of the textbook Solow growth model as follows:

$$\boldsymbol{\varepsilon}_{\mathbf{Solow}} = \phi \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \mathbf{S_A} + \frac{\alpha\phi}{1-\alpha} \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \mathbf{S_K} + \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \boldsymbol{\varepsilon} \tag{68}$$

The Solow growth model omits R&D expenditures implied by the Schumpeterian growth model of Aghion and Howitt (1998) and Howitt (2000). Its error term contains also omitted variables due to technological interdependence as also underlined by Ertur and Koch (2007) in the case of the "AK" growth model, and contains spatial error autocorrelation. The error term of the econometric reduced form proposed by Aghion and Howitt (1998) and Howitt (2000) can be also be rewritten as follows:

$$\boldsymbol{\varepsilon}_{\mathbf{AH}} = \phi \sum_{r=1}^{\infty} \gamma^r \mathbf{W}^r \mathbf{S}_{\mathbf{A}} + \frac{\alpha\phi}{1-\alpha} \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \mathbf{S}_{\mathbf{K}} + \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \boldsymbol{\varepsilon} \tag{69}$$

Therefore, although the econometric reduced form of Aghion and Howitt (1998) and Howitt (2000) contains R&D expenditures as naturally implied by the Schumpterian growth model, it omits other important variables due to technological interdependence. Indeed, their econometric specification omits *foreign* R&D expenditures at the origin of the important propriety of international R&D spillovers in the multi-country Schumpeterian growth model. Moreover, the Aghion and Howitt (1998) and Howitt (2000) error terms are spatially autocorrelated. These omissions imply that their econometric model is clearly misspecified and is estimated without using the appropriate estimation methods.

We therefore need to take into account technological interdependence between countries. To this end, under the hypothesis of normality of the error term, we first estimate the multi-country Solow growth model similar to the one proposed by Ertur and Koch (2007) in columns 3 and 4 of Table 1, using both interaction matrices **W1** and **W2** defined above. Estimation by maximum likelihood of the Spatial Error Model (SEM) corresponding to specification (58) gives results that are qualitatively similar to those of the textbook Solow growth model. Indeed, the coefficients have the expected signs and remain highly significant. Moreover, the coefficient γ measuring the degree of technological interdependence between countries, or the coefficient of spatial autocorrelation in the SEM, is significant. Therefore, countries cannot be considered as independent observations. OLS estimators remain unbiased and consistent but statistical inference based on them are biased due to the presence of spatial autocorrelation in the error term even if, in our case, the conclusions of the individual significance tests on the parameters of interest are unchanged.

Then, in the columns 5 and 6 of Table 1, again under the hypothesis of normality of the error term, we estimate by maximum likelihood our integrated multi-country Schumpeterian growth model, that is the econometric specification (39) corresponding to the unconstrained Spatial Durbin Model (SDM), using both interaction matrices **W1** and **W2** defined above. All parameters have the expected signs and are significant whatever the interaction matrix used, except the working-age population growth rate, and the lagged investment rate in physical capital divided by the effective depreciation rate when **W2** is used. The coefficient associated to the investment rate in physical capital divided by the effective depreciation rate ranges from 0.486 using **W2** to 0.671 using **W1** and is significant. The coefficient associated with the R&D expenditure decreases to 0.231 using **W1** and even to 0.175 using **W2**, but remains significant. The spatial autocorrelation parameter γ ranges from 0.080 using **W1** to 0.111 using **W2** and is significant as well showing the importance of international knowledge spillovers in growth and development processes.[14] Estimation of the model, which includes the

[14] The normalized coefficients γ^* range from 0.28 to 0.39 and are highly significant whatever the interaction matrix used.

theoretical restrictions $\phi = \beta_2 = \beta_3$ confirms the previous results. Note that our results are fairly robust with regard to the choice of the interaction matrix with a slight preference to the **W1** matrix according to the information criteria. The estimated value of γ, which measures the absorbtion capacity of the receiving country, is close to the values obtained in Benhabib and Spiegel (1994, 2005). In contrast to Aghion and Howitt (1998) and Howitt (2000), we capture all the rich interaction structures implied by the multi-country Schumpeterian growth model.

Finally, likelihood ratio tests show that the constrained Spatial Durbin Model (SDM), i.e. the Spatial Error Model (SEM), is strongly rejected in favor of the unconstrained SDM, whatever the interaction matrix considered. These results suggest that R&D expenditures play an important role in growth and development processes and are consistent with our integrated multi-country Schumpeterian growth model. In other words, the multi-country pure Solow growth model is rejected in favor of the multi-country Schumpeterian growth model, once both models are integrated in a unified theoretical and methodological framework characterized by technological interdependence. To the best of our knowledge, this question has not been resolved before in the growth literature using the traditional methodology.

International diffusion of R&D We finally estimate, by maximum likelihood, under the hypothesis of normality of the error term, the Total Factor Productivity equation implied by our multi-country Schumpeterian growth model using specification (59) as well as the international R&D spillovers implied by technological interdependence.

In Table 2, we display the estimation result of our Total Factor Productivity equation using both interaction matrices **W1** and **W2**. Only the coefficient of R&D expenditures remains significant, whereas the coefficients of the investment rate divided by the effective depreciation rate and of the working-age population growth rate are non-significant. We also note that the spatial autocorrelation parameter is significant, whatever the interaction matrix used, showing that Total Factor Productivity of one country cannot be considered as independent from that of other countries. The restricted model is estimated in the bottom part of Table 2. The linear restrictions implied by the theoretical model are not rejected. This restricted model gives some information about structural parameters. First, the parameter ϕ gives the value of the elasticity of the Poisson arrival rate with respect to the productivity-adjusted expenditure on vertical R&D in each sector. Its estimated value ranges from 0.150 to 0.159. Second, the spatial autocorrelation parameter, γ, gives the value of absorbtion capacity. Its estimated value ranges from 0.050 to 0.057 and is significant.[15]

Table 2 around here

Using the econometric results of Table 2, we quantify the impact of home and foreign R&D expenditures on the Total Factor Productivity of a given country. More precisely, using the structure of the **W2** matrix, we measure the intra-OECD R&D spillovers as Coe and Helpman, (1995) and the North-South R&D spillovers as Coe *et al.* (1997). We measure all bilateral impacts using equation (61) and we display

[15] The normalized coefficient γ^* ranges from 0.172 to 0.196 and is highly significant whatever the interaction matrix used. The econometric results therefore corroborate the importance of the role played by the international diffusion of knowledge.

all the results in Table 3. This Table is divided in two parts. The upper part displays intra OECD R&D spillovers and the lower part, the North-South R&D spillovers (from OECD countries to developing countries). We associate statistical significance using the Delta method where one, two and three stars represent a level of significance of 10%, 5% and 1% respectively. We finally note that the flow of knowledge between countries i and j goes from the country in column j to the country in row i and we represent in bold case the intra spillovers that is the elasticity of a given country with respect to its own R&D expenditures.

Table 3 around here

First, as also underlined by Coe and Helpman (1995), the effect of home R&D expenditures are slightly higher when we take into account foreign R&D expenditures because of feedback effects as we also showed theoretically. International spillovers play an important role on the level of Total Factor Productivity at steady state as expected, since all intra-OECD and North-South diffusion terms are significant. However, these effects differ in function of the specific interaction between countries.

The United States is the country which diffuses the most its R&D to other countries, followed by Germany and Japan. This is essentially due to the weight of the United States in the international trade pattern. We also note that, the United States R&D diffusion impact is high for other American countries, like Canada, Mexico, Costa Rica or Colombia for instance (in our sample, Canada imports almost 48% from the United States, Mexico, 72%; Costa Rica, 71%; and Colombia, 50%). We also note the role played by the human capital stock to enhance the absorption capacity in international R&D diffusion since the impact on Canada is more important than on Mexico although the latter has an higher import share from the United States. These results about the United States show the weight of this country in the American continent, as also underlined by Coe *et al.* (1997). The elasticities from Japan to South East Asian countries are also higher than the elasticities from Japan to other countries. These results suggest that the United States are a natural technological leader for Central and Southern American countries or that Japan is the technological leader in South East Asia.

We note that knowledge locally diffuses between European countries where elasticities are higher for larger emitting countries as Germany, France or United Kingdom than for smaller countries. High elasticities between UK and Ireland or between Germany and Austria for instance could also be due to cultural proximity or common languages. High bilateral impacts between Australia and New Zealand with respect to their Total Factor Productivity levels could be explained by similar factors. We also note that the elasticities between European and African countries are relatively high showing the importance of European countries (essentially France and United-Kingdom) as technological leaders for African countries.

These regional results are consistent with those of Coe *et al.* (1997) and highlight the heterogeneity of the international diffusion of knowledge. This empirical evidence cannot be captured by the standard Aghion and Howitt (1998) and Howitt (2000) models, which assume a *global* technological leader whereas our integrated multi-country Schumpeterian growth model allows the emergence of *local* technological leaders. Moreover, our theoretical framework may also be interpreted as providing the missing econometric reduced form for the analysis of international R&D spillovers, therefore bridging the gap in this literature between theory and empirics.

8 Conclusion

This paper shows how endogenous growth models can be structurally estimated when they include international knowledge spillovers. This idea, originally due to Aghion and Howitt (1998) and Howitt (2000), is extended to take into account richer technological interdependence patterns. Moreover, extending the methodological framework developed by Ertur and Koch (2007), we show how multi-country growth models imply spatial econometric reduced forms. We therefore elaborate a generalized multi-country Schumpeterian growth model with complete technological interactions leading to an estimable implicit spatial econometric reduced form. A structural test discriminating between the endogenous growth model motivated by R&D expenditures and the Solow growth model is then proposed. The implicit nature of the theoretical as well as the empirical models allows to recover the impact of international R&D spillovers on the level of Total Factor Productivity. Our results show that the Schumpeterian growth model is consistent with cross-country evidence and underline the importance of productivity differences along with physical capital accumulation. Moreover, we also show that the neoclassical growth model is rejected in favor of its Schumpeterian extension.

Therefore, we claim that our theoretical and methodological approaches may challenge one of the fondamental issues of the economic growth literature. Indeed, we show how they widen our vision of growth and development processes, both theoretically when we consider multi-country modeling, and empirically when technological interdependence is fully taken into account using the appropriate spatial econometric estimation methods.

The interaction matrices we use are to be considered as a first attempt to model the complex connectivity patterns linking countries. Future research could deepen the analysis and propose some sound theoretical foundations to design such matrices. The theoretical literature on social interactions, surveyed by Brock and Durlauf (2001) or Manski (2000) among others, could be an interesting source for "cross-fertilization". As Durlauf et al. (2005), we believe that such interaction based models may provide firm microfoundations for cross section dependence in growth and development contexts, even if the presence of such spillovers has some consequences for identification that may be difficult to resolve (Blume and Durlauf, 2005; Manski, 1993).

Finally, this paper is based on the idea of parallel long run growth paths. Recent developments of the Schumpeterian growth theory suggest to generalize our framework to take into account non-parallel long run ways of growth (Howitt and Mayer-Foulkes, 2005; Acemoglu *et al.*, 2006) allowing richer club structures. Our structural approach seems promising to estimate and test theoretical predictions of such models.

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Table 1 The multi-country Solow model v.s. the multi-country Schumpeterian model

Models	Solow	AH	m-c Solow		m-c Schumpeter	
Estimation method	OLS	OLS	ML		ML	
Weights matrix			(**W1**)	(**W2**)	(**W1**)	(**W2**)
Unrestricted Model						
constant	3.813	3.585	3.783	3.383	4.458	4.143
	(0.000)	(0.019)	(0.000)	(0.000)	(0.000)	(0.001)
$\ln s_{K,i} - \ln(n_i + 0.05)$	1.181	0.632	1.172	0.658	0.671	0.486
	(0.000)	(0.004)	(0.000)	(0.000)	(0.000)	(0.001)
$\ln s_{A,i}$	—	0.275	—	—	0.231	0.175
		(0.001)			(0.000)	(0.006)
$\ln n_i$	—	-0.811	—	—	0.223	0.121
		(0.382)			(0.797)	(0.892)
$\mathbf{W}(\ln s_{K,j} - \ln(n_j + 0.05))$	—	—	—	—	-0.314	-0.437
					(0.000)	(0.282)
γ	—	—	0.151	0.286	0.080	0.111
			(0.017)	(0.000)	(0.000)	(0.000)
LR test	—	—	—	—	39.725	16.749
					(0.000)	(0.000)
R^2 or Pseudo$-R^2$	0.541	0.706	0.541	0.541	0.787	0.759
$\bar{R}^2$	0.533	0.690	—	—	—	—
AIC	-0.417	-0.794	-0.491	-0.783	-1.062	-0.966
BIC	-0.346	-0.653	-0.420	-0.713	-0.886	-0.790
Restricted Model						
constant	—	5.265	—	—	4.463	4.219
		(0.000)			(0.000)	(0.000)
$\ln s_{K,i} - \ln(n_i + 0.05)$	—	0.678	—	—	0.670	0.487
		(0.003)			(0.000)	(0.001)
$\ln s_{A,i} + \ln n_i$	—	0.311	—	—	0.231	0.176
		(0.000)			(0.000)	(0.004)
$\mathbf{W}(\ln s_{K,j} - \ln(n_j + 0.05))$	—	—	—	—	-0.316	-0.443
					(0.000)	(0.277)
γ	—	—	—	—	0.081	0.113
					(0.000)	(0.032)
LR test	—	—	—	—	39.723	16.746
					(0.000)	(0.000)
R^2 or Pseudo$-R^2$	—	0.699	—	—	0.787	0.759
$\bar{R}^2$	—	0.688	—	—	—	—
AIC	—	-0.805	—	—	-1.096	-0.999
BIC	—	-0.700	—	—	-0.955	-0.859

Notes: p-values are in parentheses. OLS estimation is implemented using the heteroscedasticity consistent covariance matrix estimator of White (1980). AIC is the Akaike information criterion. BIC is the Schwarz information criterion. Pseudo$-R^2$ is the squared correlation between predicted and actual values. LR is the likelihood ratio test of the multi-country Solow growth model versus the multi-country Schumpeterian growth model.

Table 2 Total Factor Productivity

Estimation method Weights matrix	ML (**W1**)	ML (**W2**)
Unrestricted model		
constant	4.104	4.035
	(0.003)	(0.002)
$\ln s_{K,i} - \ln(n_i + 0.05)$	-0.035	-0.110
	(0.907)	(0.709)
$\ln n_i$	0.036	0.067
	(0.970)	(0.940)
$\ln s_{A,i}$	0.174	0.170
	(0.012)	(0.008)
γ	0.051	0.060
	(0.000)	(0.000)
Pseudo$-R^2$	0.603	0.616
AIC	-0.929	-0.984
BIC	-0.788	-0.843
Restricted model		
constant	4.220	4.082
	(0.000)	(0.000)
$\ln s_{A,i} + \ln n_i + \ln s_{K,i} - \ln(n_i + 0.05)$	0.159	0.150
	(0.012)	(0.004)
γ	0.050	0.057
	(0.002)	(0.000)
Test of restrictions (LR)	0.449	0.819
	(0.930)	(0.845)
Pseudo$-R^2$	0.598	0.609
AIC	-0.989	-1.038
BIC	-0.919	-0.967

Notes: p-values are in parentheses. AIC is the Akaike information criterion. BIC is the Schwarz information criterion. Pseudo$-R^2$ is the linear correlation coefficient between observed explained variable and estimated explained variable. LR is the likelihood ratio test for the theoretical linear restrictions.

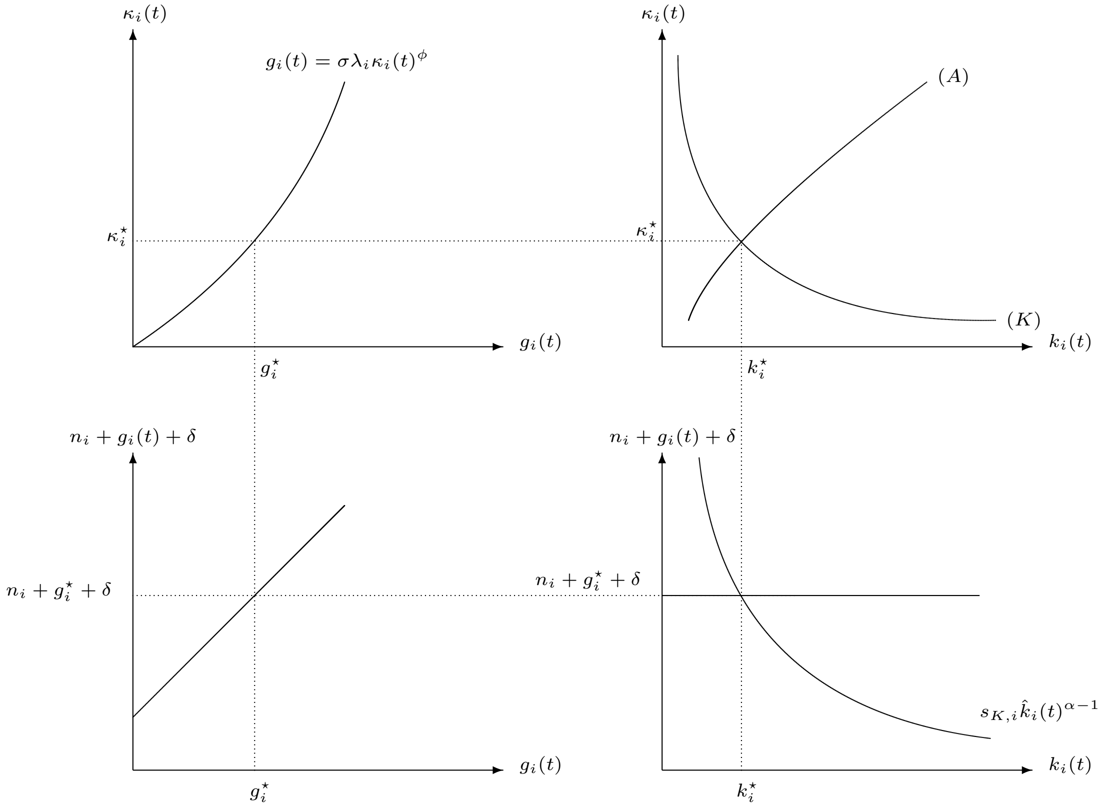

Fig. 1 Steady-state in the one country Schumpeterian growth model

Appendix 1: Elasticities

To resolve equation (31) for $\mathbf{y}$, we subtract $\gamma\mathbf{Wy}$ from both sides and we premultiply both sides by $(\mathbf{I}-\gamma\mathbf{W})^{-1}$ to obtain:

$$\mathbf{y} = \left(\ln \frac{\sigma}{g((1+\sigma)\xi)^{\phi}} (\mathbf{I}-\gamma\mathbf{W})^{-1} \mathbb{1}_{(\mathbf{n},\mathbf{1})}\right) + \phi (\mathbf{I}-\gamma\mathbf{W})^{-1} (\mathbf{s_A}+\mathbf{n}) + \frac{\alpha}{1-\alpha}\mathbf{S_K} + \frac{\alpha\phi}{1-\alpha} (\mathbf{I}-\gamma\mathbf{W})^{-1} \mathbf{S_K}$$

We derive with respect to $\mathbf{s_A}$ in order to obtain the matrix of elasticities of R&D investment rates, reflecting the international R&D spillovers:

$$\mathbf{\Xi}^{\mathbf{s_A}} \equiv \frac{\partial \mathbf{y}}{\partial \mathbf{s_A}} = \phi (\mathbf{I}-\gamma\mathbf{W})^{-1} = \phi\mathbf{I} + \phi\sum_{r=1}^{\infty}\gamma^r\mathbf{W}^r$$

We derive with respect to $\mathbf{s_K}$ in order to obtain the matrix of elasticities of investment rates in the physical capital accumulation sector, reflecting the international diffusion effect of knowledge:

$$\mathbf{\Xi}^{\mathbf{s_K}} \equiv \frac{\partial \mathbf{y}}{\partial \mathbf{s_K}} = \frac{\alpha}{1-\alpha}\mathbf{I} + \frac{\alpha\phi}{1-\alpha} (\mathbf{I}-\gamma\mathbf{W})^{-1} = \frac{\alpha(1+\phi)}{1-\alpha}\mathbf{I} + \frac{\alpha\phi}{1-\alpha}\sum_{r=1}^{\infty}\gamma^r\mathbf{W}^r$$

Finally, we derive with respect to $\mathbf{n}$ in order to obtain the matrix of elasticities of working-age population growth rates, reflecting the positive impact of horizontal differentiation and the negative impact of physical capital dilution:

$$\mathbf{\Xi}^{\mathbf{n}} \equiv \frac{\partial \mathbf{y}}{\partial \mathbf{n}} = -\frac{\alpha}{1-\alpha}\mathbf{diag}\left(\frac{\mathbf{n}}{\mathbf{n}+\mathbf{g}+\boldsymbol{\delta}}\right) + \frac{\alpha\phi}{1-\alpha}\mathbf{diag}\left(\frac{\mathbf{g}+\boldsymbol{\delta}}{\mathbf{n}+\mathbf{g}+\boldsymbol{\delta}}\right) + \frac{\alpha\phi}{1-\alpha}\sum_{r=1}^{\infty}\gamma^r\mathbf{W}^{\mathbf{r}}\mathbf{diag}\left(\frac{\mathbf{g}+\boldsymbol{\delta}}{\mathbf{n}+\mathbf{g}+\boldsymbol{\delta}}\right)$$

where $\mathbf{diag}\left(\frac{\mathbf{n}}{\mathbf{n}+\mathbf{g}+\boldsymbol{\delta}}\right)$ and $\mathbf{diag}\left(\frac{\mathbf{g}+\boldsymbol{\delta}}{\mathbf{n}+\mathbf{g}+\boldsymbol{\delta}}\right)$ are two $(n \times n)$ diagonal matrices with respectively the general terms: $\frac{n_i}{n_i+g_w+\delta}$ and $\frac{g_w+\delta}{n_i+g_w+\delta}$ for $i = 1, ..., n$.

Appendix 2: General interaction patterns

Let us consider some potential interaction patterns between countries, which may be incorporated in the **W** matrix. In order to visualize them, let us consider 5 interdependent countries. We first present the more complete structure of interaction between countries that it is possible to consider. In order to use analytically this complete structure of interaction, we represent it in the following (5×5) matrix:

$$\mathbf{W} = \left(\begin{array}{ccc|cc} 0 & w_{12} & w_{13} & w_{14} & w_{15} \\ w_{21} & 0 & w_{23} & w_{24} & w_{25} \\ w_{31} & w_{32} & 0 & w_{34} & w_{35} \\ \hline w_{41} & w_{42} & w_{43} & 0 & w_{45} \\ w_{51} & w_{52} & w_{53} & w_{54} & 0 \end{array}\right) = \begin{pmatrix} \mathbf{W_{11}} & \mathbf{W_{12}} \\ \mathbf{W_{21}} & \mathbf{W_{22}} \end{pmatrix}$$

The flows of knowledge between countries go from country j to country i (for instance w_{23} represents the flow from country 3 to country 2). In other words, each row represents the receiving country and each column represents the emitting country. When countries are regrouped in clubs, the **W** matrix has a particular structure. Assume that the first to the third countries belong to the club 1 and the two last countries belong to the club 2. The **W** matrix has then a bloc structure.

The four sub-matrices represent different diffusion patterns. First, the sub-matrices $\mathbf{W_{11}}$ and $\mathbf{W_{22}}$ on the main bloc-diagonal represent the intra-club diffusion. Second, the sub-matrix $\mathbf{W_{12}}$ represents the diffusion from countries in the club 2 to the countries in the club 1, whereas the sub-matrix $\mathbf{W_{21}}$ represents the diffusion from countries in the club 1 to the countries in the club 2. The technological multiplier effect is represented by the successive powers of the interaction matrix. As already mentioned, it is represented by equation (45).

To be more specific, let us now consider two particular cases that are used in the literature: diffusion from a technological leader and intra-club diffusion where in addition the North club diffuses its knowledge to the South club.

The technological leader We first consider the case where there is a technological leader which diffuses its knowledge to other countries. We assume in our example that country 5 is the technological leader and countries 1, 2, 3 and 4 are technological followers. The matrix of interactions is then defined as follows:

$$\mathbf{W} = \left(\begin{array}{cccc|c} 0 & 0 & 0 & 0 & w_{15} \\ 0 & 0 & 0 & 0 & w_{25} \\ 0 & 0 & 0 & 0 & w_{35} \\ 0 & 0 & 0 & 0 & w_{45} \\ \hline 0 & 0 & 0 & 0 & 0 \end{array}\right) = \begin{pmatrix} \mathbf{0} & \mathbf{W_{12}} \\ \mathbf{0} & 0 \end{pmatrix}$$

Only the last column representing the diffusion from country 5 to other countries has non null terms. The technological multiplier effect is therefore defined as:

$$(\mathbf{I} - \gamma \mathbf{W})^{-1} = \begin{pmatrix} \mathbf{I_{11}} & \gamma \mathbf{W_{12}} \\ \mathbf{0} & 1 \end{pmatrix}$$

Since there is no feedback effect from technological followers to the technological leader, the latter does not beneficiate from foreign technology. Only the technological followers beneficiates from the technological leader.

Note that the literature based on the concept of technological leader generally focuses on the capacity of absorption of the receiving country. For instance, the model developed by Benhabib and Spiegel (1994) along the lines of Nelson and Phelps (1966), can be interpreted in our theoretical framework. In other words, their model is a particular case of the model developed in this paper, and should therefore be estimated using the appropriate spatial econometric methods.

Clubs with north-south diffusion Define the club 1 as the South club and the club 2 as the North Club. Countries 1, 2 and 3 belong to the South club and countries 4 and 5 belong to the North club. Assume that the North club diffuses its knowledge to the South club, but the south club does not. The $\mathbf{W}$ matrix representing this case has therefore a bloc triangular structure as follows:

$$\mathbf{W} = \left(\begin{array}{ccc|cc} 0 & w_{12} & w_{13} & w_{14} & w_{15} \\ w_{21} & 0 & w_{23} & w_{24} & w_{25} \\ w_{31} & w_{32} & 0 & w_{34} & w_{35} \\ \hline 0 & 0 & 0 & 0 & w_{45} \\ 0 & 0 & 0 & w_{54} & 0 \end{array}\right) = \begin{pmatrix} \mathbf{W_{11}} & \mathbf{W_{12}} \\ 0 & \mathbf{W_{22}} \end{pmatrix}$$

We note that these terms are 0 for the relations from club 1 (the South club) to club 2 (the North club) reflecting the fact that poor countries do not diffuse knowledge to rich countries. Terms belonging to the $\mathbf{W_{12}}$ sub-matrix represent the North-South diffusion of knowledge. International R&D spillovers between OECD countries, that is inside the North club, can be considered using the $\mathbf{W_{22}}$ matrix whereas the North-South R&D diffusion can be considered using the $\mathbf{W_{12}}$ matrix. We propose, in contrast to the literature devoted to international R&D spillovers, to simultaneously consider both intra-OECD and North-South R&D spillovers along with their indirect effects using the richer structure of the technological multiplier.

The implied technological multiplier needs to be carefully analyzed. Using the inverse of partitioned matrix, we easily obtain :

$$(\mathbf{I} - \gamma\mathbf{W})^{-1} = \begin{pmatrix} (\mathbf{I_3} - \gamma\mathbf{W_{11}})^{-1} & \gamma(\mathbf{I_3} - \gamma\mathbf{W_{11}})^{-1}\mathbf{W_{12}}(\mathbf{I_2} - \gamma\mathbf{W_{22}})^{-1} \\ \mathbf{0} & (\mathbf{I_2} - \gamma\mathbf{W_{22}})^{-1} \end{pmatrix}$$

In the main block diagonal we obtain the effect of intra-club diffusion of knowledge. The most interesting term is the off-diagonal block term representing the inter-clubs diffusion or in other words the North-South diffusion of knowledge. Developing this term and rearranging it, we have:

$$\gamma \sum_{r=0}^{\infty} \sum_{s=0}^{\infty} \gamma^r \gamma^s \mathbf{W_{11}^r} \mathbf{W_{12}} \mathbf{W_{22}^s} \tag{70}$$

Different types of diffusion can be expressed in relation to the sum of the exponents r and s. First, when $s + r = 0$, that is $r = 0$ and $s = 0$, we obtain $\gamma\mathbf{W_{12}}$, which corresponds to the direct diffusion of knowledge from the North club to the South club. Second, when $r + s = 1$, that is either $r = 1$ or $s = 1$, we obtain $\gamma^2(\mathbf{W_{12}}\mathbf{W_{22}} + \mathbf{W_{11}}\mathbf{W_{12}})$ which corresponds to one type of the indirect diffusion of knowledge. The first part of this expression, that is $\gamma^2\mathbf{W_{12}}\mathbf{W_{22}}$, represents the diffusion inside the North club ($\mathbf{W_{22}}$) retransmitted to the South club ($\mathbf{W_{12}}$). For instance, a technology is diffused from the United States to an European country, which in turn diffuses it to an African country. The second part of this expression represents the intra-South club diffusion ($\mathbf{W_{11}}$) retransmitted from the North club ($\mathbf{W_{12}}$). For instance, the United States diffuses a technology to South Africa which in turn diffuses it to other African countries.

It is further possible to express higher degrees of indirect diffusion based on the sum of the exponents r and s. For instance, when $r + s = 2$, we have an indirect diffusion of degree 2: an example is the case where the United States diffuses a technology to an European country, which in turn diffuses it to an another European country, which finally diffuses it to an African country.

This type of interaction structure is of great interest for the literature on international diffusion of R&D. Indeed, it encompasses different particular cases studied for instance by Coe and Helpman (1995) or Coe *et al.* (1997). In the first paper, only the diffusion of R&D between OECD countries is considered that is diffusion inside the North club ($\mathbf{W_{22}}$ in our notations). In the second paper, only the North-South diffusion of R&D is considered ($\mathbf{W_{12}}$ in our notation). To the best of our knowledge, only Lumenga-Neso *et al.* (2005) have recently suggested an empirical approach to deal with indirect effects. We propose here a generalization which allows considering any type of direct and indirect diffusions in an unified theoretical and methodological framework.

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Table 3 International R&D spillovers

	AUS	AUT	BEL	CAN	DNK	FIN
AUS	**0.1707*****	0.0003**	0.0007**	0.0012**	0.0003**	0.0004***
AUT	0.0001*	**0.1706*****	0.0014**	0.0003**	0.0004**	0.0004***
BEL	0.0002**	0.0004**	**0.1708*****	0.0003**	0.0003**	0.0003**
CAN	0.0007**	0.0003**	0.0006**	**0.1707*****	0.0003**	0.0003**
DNK	0.0001**	0.0006**	0.0017***	0.0003**	**0.1705*****	0.0012***
FIN	0.0003**	0.0006***	0.0014**	0.0004**	0.0015***	0.1705***
FRA	0.0002**	0.0005**	0.0034***	0.0004**	0.0004**	0.0004***
GER	0.0002**	0.0020***	0.0032***	0.0005**	0.0010***	0.0006***
GRC	0.0001**	0.0005**	0.0015***	0.0002**	0.0005***	0.0004***
IRL	0.0001**	0.0002**	0.0008**	0.0004**	0.0004**	0.0003**
ITA	0.0002**	0.0009***	0.0020***	0.0004**	0.0004***	0.0003**
JPN	0.0031***	0.0003**	0.0007**	0.0022***	0.0005***	0.0002**
KOR	0.0021***	0.0002**	0.0005**	0.0012**	0.0002**	0.0002**
NLD	0.0002**	0.0005**	0.0047***	0.0004**	0.0006***	0.0005***
NZL	0.0093***	0.0002**	0.0006**	0.0010**	0.0003**	0.0003**
NOR	0.0002**	0.0005**	0.0013**	0.0009***	0.0030***	0.0015***
PRT	0.0001**	0.0002**	0.0011***	0.0001**	0.0002**	0.0002**
ESP	0.0001**	0.0004**	0.0014***	0.0002**	0.0003**	0.0003***
SWE	0.0002**	0.0006**	0.0017***	0.0003**	0.0029***	0.0023***
CHE	0.0001**	0.0018***	0.0019**	0.0003**	0.0005**	0.0004**
GBR	0.0004**	0.0004**	0.0023***	0.0008***	0.0007***	0.0006***
USA	0.0009***	0.0005**	0.0015**	0.0028***	0.0005**	0.0004***
ARG	0.0003**	0.0003**	0.0009**	0.0007**	0.0002**	0.0003**
BOL	0.0001*	0.0002**	0.0004**	0.0007**	0.0002**	0.0002**
BRA	0.0003**	0.0002**	0.0006**	0.0009***	0.0002**	0.0002**
BFA	0.0001**	0.0001**	0.0007***	0.0002**	0.0002***	0.0000**
CHL	0.0005**	0.0002**	0.0006**	0.0014***	0.0003**	0.0004***
CHN	0.0008***	0.0001**	0.0003**	0.0007***	0.0001**	0.0002***
COL	0.0002**	0.0001**	0.0004**	0.0012***	0.0001**	0.0002**
CRI	0.0001*	0.0001**	0.0003**	0.0005**	0.0001**	0.0001**
CUB	0.0001*	0.0001**	0.0009**	0.0033***	0.0002**	0.0001**
CYP	0.0001**	0.0003**	0.0008**	0.0002**	0.0004***	0.0002**
ECU	0.0002**	0.0001**	0.0006**	0.0009**	0.0001**	0.0001**
EGY	0.0003**	0.0002**	0.0006**	0.0003**	0.0002***	0.0003***
SLV	0.0001**	0.0001**	0.0002**	0.0004**	0.0001**	0.0002***
HND	0.0001*	0.0001*	0.0002**	0.0004**	0.0001**	0.0001**
HUN	0.0001*	0.0042***	0.0013**	0.0002**	0.0003**	0.0005***
IND	0.0010***	0.0001**	0.0020***	0.0004***	0.0002**	0.0001**
JAM	0.0002**	0.0001*	0.0004**	0.0011***	0.0003**	0.0001**
MDG	0.0001**	0.0001**	0.0008***	0.0001**	0.0001**	0.0000**
MYS	0.0012***	0.0001**	0.0004**	0.0005**	0.0001**	0.0001**
MUS	0.0013***	0.0001**	0.0011**	0.0001**	0.0002**	0.0001**
MEX	0.0002**	0.0001**	0.0003**	0.0009**	0.0001**	0.0001**
NIC	0.0001**	0.0001**	0.0003**	0.0006**	0.0002**	0.0002***
PAN	0.0003*	0.0001*	0.0002**	0.0003**	0.0002**	0.0001**
PRY	0.0001*	0.0001**	0.0003**	0.0003**	0.0001**	0.0001*
PER	0.0003**	0.0002**	0.0006**	0.0012***	0.0002**	0.0002**
PHL	0.0012***	0.0001**	0.0004**	0.0006**	0.0001**	0.0002**
ROM	0.0004***	0.0014***	0.0010**	0.0003**	0.0003**	0.0002**
SGP	0.0008***	0.0001**	0.0004**	0.0004**	0.0001**	0.0002**
ZAF	0.0006***	0.0003**	0.0008**	0.0004**	0.0002**	0.0003***
SYR	0.0001*	0.0004***	0.0012***	0.0002**	0.0002**	0.0002***
THA	0.0009***	0.0001**	0.0005**	0.0005**	0.0002**	0.0002***
TTO	0.0004**	0.0001**	0.0005**	0.0018***	0.0001**	0.0001**
TUN	0.0000*	0.0001**	0.0009***	0.0002**	0.0001**	0.0001**
TUR	0.0002**	0.0004***	0.0009**	0.0002**	0.0002**	0.0003***
UGA	0.0001**	0.0002**	0.0008***	0.0004***	0.0003***	0.0001**
URY	0.0002**	0.0002**	0.0005**	0.0005**	0.0003**	0.0001**
VEN	0.0001**	0.0001**	0.0005**	0.0010***	0.0001**	0.0001**

Table 3 International R&D spillovers (continued)

	FRA	GER	GRC	IRL	ITA	JPN
AUS	0.0018**	0.0041**	0.0001**	0.0005**	0.0019**	0.0080***
AUT	0.0026**	0.0164***	0.0001***	0.0003**	0.0037***	0.0016**
BEL	0.0056***	0.0078***	0.0001**	0.0006***	0.0019**	0.0012**
CAN	0.0021**	0.0033**	0.0001**	0.0004**	0.0017**	0.0056***
DNK	0.0028**	0.0095***	0.0001**	0.0005**	0.0021***	0.0014**
FIN	0.0023**	0.0071***	0.0001***	0.0005**	0.0020***	0.0027***
FRA	**0.1711*****	0.0073***	0.0001***	0.0006***	0.0040***	0.0017***
GER	0.0057***	**0.1720*****	0.0002***	0.0008***	0.0043***	0.0029***
GRC	0.0033***	0.0064***	**0.1704*****	0.0004**	0.0056***	0.0018***
IRL	0.0020**	0.0034**	0.0000**	**0.1705*****	0.0012**	0.0024***
ITA	0.0053***	0.0077***	0.0003***	0.0005**	**0.1709*****	0.0012**
JPN	0.0020**	0.0037**	0.0000**	0.0006**	0.0017**	0.1712***
KOR	0.0012**	0.0029**	0.0000**	0.0003**	0.0011**	0.0105***
NLD	0.0035***	0.0091***	0.0001**	0.0007***	0.0018**	0.0020***
NZL	0.0013**	0.0028**	0.0000**	0.0003**	0.0013**	0.0063***
NOR	0.0023**	0.0065***	0.0001**	0.0006***	0.0019**	0.0024***
PRT	0.0032***	0.0042***	0.0000**	0.0002**	0.0023***	0.0008**
ESP	0.0059***	0.0058***	0.0001***	0.0005***	0.0034***	0.0014***
SWE	0.0028**	0.0081***	0.0001***	0.0006***	0.0018**	0.0017**
CHE	0.0053***	0.0138***	0.0001**	0.0007***	0.0046***	0.0018**
GBR	0.0044***	0.0069***	0.0001***	0.0017***	0.0026***	0.0026***
USA	0.0038***	0.0076***	0.0001***	0.0010***	0.0033***	0.0034***
ARG	0.0029***	0.0039***	0.0000**	0.0002**	0.0030***	0.0023***
BOL	0.0012**	0.0029**	0.0000**	0.0002**	0.0016***	0.0031***
BRA	0.0014**	0.0038***	0.0000**	0.0002**	0.0020***	0.0022***
BFA	0.0063***	0.0008**	0.0000**	0.0001**	0.0007**	0.0008***
CHL	0.0020**	0.0033**	0.0000**	0.0002**	0.0020***	0.0035***
CHN	0.0009**	0.0021**	0.0000**	0.0001**	0.0008**	0.0063***
COL	0.0013**	0.0024**	0.0000**	0.0001**	0.0011**	0.0026***
CRI	0.0010**	0.0015**	0.0000*	0.0002**	0.0008**	0.0016***
CUB	0.0033***	0.0017**	0.0000**	0.0001**	0.0026***	0.0007**
CYP	0.0020**	0.0044***	0.0028***	0.0003**	0.0032***	0.0027***
ECU	0.0010**	0.0026**	0.0000*	0.0001**	0.0017***	0.0036***
EGY	0.0022***	0.0029***	0.0002***	0.0003***	0.0023***	0.0014***
SLV	0.0011**	0.0015**	0.0000*	0.0001**	0.0006**	0.0013***
HND	0.0006**	0.0011**	0.0001***	0.0001**	0.0005**	0.0013**
HUN	0.0023**	0.0118***	0.0001***	0.0003**	0.0034***	0.0017***
IND	0.0009**	0.0025***	0.0000**	0.0001**	0.0008**	0.0020***
JAM	0.0012**	0.0014**	0.0000**	0.0002**	0.0009**	0.0017**
MDG	0.0085***	0.0013**	0.0000**	0.0001**	0.0008**	0.0013***
MYS	0.0011**	0.0022**	0.0000*	0.0003**	0.0007**	0.0089***
MUS	0.0082***	0.0027**	0.0001***	0.0003**	0.0017***	0.0022***
MEX	0.0009**	0.0022**	0.0000**	0.0002**	0.0008**	0.0019***
NIC	0.0009**	0.0013**	0.0000**	0.0001**	0.0007**	0.0027***
PAN	0.0007**	0.0011**	0.0001***	0.0001*	0.0014***	0.0140***
PRY	0.0010**	0.0018**	0.0000**	0.0003**	0.0013**	0.0028***
PER	0.0012**	0.0025**	0.0000**	0.0002**	0.0013**	0.0031***
PHL	0.0009**	0.0019**	0.0000**	0.0003**	0.0006**	0.0082***
ROM	0.0032***	0.0083***	0.0007***	0.0002**	0.0064***	0.0008**
SGP	0.0013**	0.0021**	0.0000**	0.0002**	0.0009**	0.0078***
ZAF	0.0015**	0.0048***	0.0000**	0.0003**	0.0014***	0.0028***
SYR	0.0026***	0.0036***	0.0003***	0.0001**	0.0033***	0.0021***
THA	0.0010**	0.0023**	0.0000**	0.0001**	0.0007**	0.0095***
TTO	0.0010**	0.0023**	0.0000**	0.0004**	0.0010**	0.0022***
TUN	0.0048***	0.0027***	0.0001***	0.0001**	0.0033***	0.0005**
TUR	0.0021***	0.0049***	0.0002***	0.0002**	0.0026***	0.0013***
UGA	0.0016***	0.0019**	0.0000***	0.0003**	0.0012***	0.0022***
URY	0.0031***	0.0029**	0.0001***	0.0002**	0.0035***	0.0020***
VEN	0.0010**	0.0021**	0.0000*	0.0001**	0.0016***	0.0016***

Table 3 International R&D spillovers (continued)

	KOR	NLD	NZL	NOR	PRT	ESP
AUS	0.0020***	0.0009**	0.0022***	0.0002**	0.0001**	0.0005**
AUT	0.0003**	0.0017**	0.0000**	0.0002**	0.0003**	0.0008**
BEL	0.0003**	0.0062***	0.0001**	0.0004**	0.0002**	0.0008**
CAN	0.0017**	0.0007**	0.0002**	0.0011***	0.0001**	0.0005**
DNK	0.0004**	0.0032***	0.0001**	0.0020***	0.0005***	0.0007**
FIN	0.0005**	0.0019**	0.0000**	0.0017***	0.0004***	0.0007**
FRA	0.0004**	0.0023***	0.0000**	0.0007***	0.0005***	0.0024***
GER	0.0006**	0.0045***	0.0001**	0.0009***	0.0005***	0.0017***
GRC	0.0008***	0.0026***	0.0001**	0.0002**	0.0002**	0.0012***
IRL	0.0006**	0.0015**	0.0000**	0.0006***	0.0002**	0.0006**
ITA	0.0003**	0.0025***	0.0001**	0.0003**	0.0002**	0.0016***
JPN	0.0035***	0.0007**	0.0005***	0.0003**	0.0001**	0.0004**
KOR	**0.1708*****	0.0006**	0.0003***	0.0002**	0.0000*	0.0003**
NLD	0.0005**	**0.1709*****	0.0000**	0.0009***	0.0003***	0.0010***
NZL	0.0012**	0.0007**	**0.1705*****	0.0002**	0.0001**	0.0003**
NOR	0.0006**	0.0022***	0.0000**	**0.1706*****	0.0004***	0.0008**
PRT	0.0003**	0.0014***	0.0000**	0.0004***	**0.1704*****	0.0050***
ESP	0.0004**	0.0016***	0.0000**	0.0003**	0.0009***	**0.1706*****
SWE	0.0004**	0.0029***	0.0000**	0.0029***	0.0004***	0.0008**
CHE	0.0004**	0.0025***	0.0000**	0.0003**	0.0003**	0.0009**
GBR	0.0007**	0.0033***	0.0002***	0.0012***	0.0004***	0.0013***
USA	0.0040***	0.0016**	0.0003***	0.0006***	0.0002**	0.0009**
ARG	0.0013***	0.0008**	0.0001**	0.0001**	0.0001**	0.0019***
BOL	0.0008**	0.0005**	0.0001**	0.0002**	0.0001**	0.0013***
BRA	0.0009**	0.0007**	0.0001**	0.0002**	0.0001**	0.0007***
BFA	0.0001**	0.0006**	0.0000*	0.0001**	0.0000**	0.0004***
CHL	0.0018***	0.0006**	0.0002***	0.0002**	0.0001**	0.0015***
CHN	0.0026***	0.0004**	0.0001**	0.0001**	0.0000**	0.0002**
COL	0.0008**	0.0005**	0.0000**	0.0001**	0.0000**	0.0008***
CRI	0.0010**	0.0004**	0.0000**	0.0001**	0.0000**	0.0005***
CUB	0.0001*	0.0010***	0.0003***	0.0001**	0.0001**	0.0070***
CYP	0.0018***	0.0010**	0.0001**	0.0005***	0.0002**	0.0010***
ECU	0.0010**	0.0006**	0.0001**	0.0001*	0.0001**	0.0012***
EGY	0.0008***	0.0007**	0.0001***	0.0001**	0.0001**	0.0006***
SLV	0.0008**	0.0003**	0.0002***	0.0001*	0.0000**	0.0004**
HND	0.0012**	0.0004**	0.0000**	0.0001*	0.0000*	0.0005***
HUN	0.0005**	0.0016**	0.0000*	0.0002**	0.0002**	0.0007**
IND	0.0008***	0.0006**	0.0001**	0.0001**	0.0000**	0.0002**
JAM	0.0008**	0.0007**	0.0002***	0.0005***	0.0000*	0.0010***
MDG	0.0003***	0.0004**	0.0000**	0.0001*	0.0001**	0.0004**
MYS	0.0019***	0.0005**	0.0002***	0.0001**	0.0000**	0.0002**
MUS	0.0007***	0.0005**	0.0005***	0.0001*	0.0001**	0.0005**
MEX	0.0009**	0.0003**	0.0001**	0.0001*	0.0000*	0.0005**
NIC	0.0013***	0.0005**	0.0001**	0.0001**	0.0000**	0.0010***
PAN	0.0045***	0.0002*	0.0001**	0.0003***	0.0000**	0.0004***
PRY	0.0017***	0.0004**	0.0000*	0.0001*	0.0001**	0.0005***
PER	0.0015***	0.0005**	0.0004***	0.0001**	0.0000*	0.0012***
PHL	0.0026***	0.0006**	0.0003***	0.0001*	0.0000*	0.0002**
ROM	0.0011***	0.0014**	0.0000**	0.0002**	0.0001**	0.0006**
SGP	0.0017***	0.0006**	0.0001**	0.0001**	0.0000**	0.0003**
ZAF	0.0006**	0.0010**	0.0001**	0.0001**	0.0001**	0.0004**
SYR	0.0016***	0.0010**	0.0000**	0.0001**	0.0001**	0.0007***
THA	0.0015***	0.0005**	0.0002**	0.0001**	0.0000**	0.0002**
TTO	0.0009**	0.0007**	0.0002***	0.0001**	0.0001**	0.0004**
TUN	0.0002**	0.0006**	0.0000**	0.0001**	0.0001**	0.0008***
TUR	0.0006***	0.0011**	0.0001**	0.0002**	0.0001**	0.0007***
UGA	0.0004**	0.0007**	0.0000**	0.0003***	0.0000**	0.0004***
URY	0.0016***	0.0007**	0.0001**	0.0001**	0.0001**	0.0025***
VEN	0.0006**	0.0006**	0.0002***	0.0001**	0.0001**	0.0007***

Table 3 International R&D spillovers (continued)

	SWE	CHE	GBR	USA
AUS	0.0010***	0.0008**	0.0037***	0.0121***
AUT	0.0008**	0.0016***	0.0017**	0.0025**
BEL	0.0010***	0.0007**	0.0035***	0.0029**
CAN	0.0007**	0.0006**	0.0033***	0.0171***
DNK	0.0047***	0.0008**	0.0035***	0.0026**
FIN	0.0047***	0.0009**	0.0037***	0.0036***
FRA	0.0007**	0.0011***	0.0035***	0.0038***
GER	0.0012***	0.0020***	0.0038***	0.0043***
GRC	0.0007***	0.0008**	0.0025***	0.0019**
IRL	0.0006**	0.0005**	0.0122***	0.0062***
ITA	0.0007**	0.0016***	0.0026***	0.0024**
JPN	0.0007**	0.0010***	0.0021**	0.0152***
KOR	0.0004**	0.0007**	0.0014**	0.0112***
NLD	0.0012***	0.0008**	0.0042***	0.0044***
NZL	0.0008***	0.0006**	0.0028***	0.0086***
NOR	0.0062***	0.0007**	0.0043***	0.0037**
PRT	0.0004**	0.0005**	0.0019***	0.0012**
ESP	0.0006***	0.0006**	0.0029***	0.0027***
SWE	**0.1707*****	0.0009**	0.0042***	0.0034***
CHE	0.0009**	**0.1707*****	0.0031***	0.0037***
GBR	0.0013***	0.0014***	**0.1711*****	0.0059***
USA	0.0012***	0.0014***	0.0052***	**0.1718*****
ARG	0.0007***	0.0007**	0.0015**	0.0101***
BOL	0.0011***	0.0005**	0.0011**	0.0109***
BRA	0.0006***	0.0007***	0.0012**	0.0082***
BFA	0.0001*	0.0001**	0.0006**	0.0009**
CHL	0.0009***	0.0006**	0.0014**	0.0115***
CHN	0.0004**	0.0003**	0.0008**	0.0043***
COL	0.0004**	0.0006***	0.0011**	0.0103***
CRI	0.0002**	0.0003**	0.0009**	0.0146***
CUB	0.0003**	0.0003**	0.0010**	0.0008*
CYP	0.0005**	0.0005**	0.0036***	0.0022**
ECU	0.0003**	0.0006**	0.0009**	0.0122***
EGY	0.0005***	0.0005**	0.0013**	0.0050***
SLV	0.0002**	0.0003**	0.0007**	0.0116***
HND	0.0002**	0.0004**	0.0007**	0.0146***
HUN	0.0007***	0.0011***	0.0018**	0.0021**
IND	0.0003**	0.0012***	0.0020***	0.0032***
JAM	0.0003**	0.0004**	0.0017**	0.0168***
MDG	0.0001**	0.0002**	0.0007**	0.0013**
MYS	0.0004**	0.0006***	0.0014**	0.0071***
MUS	0.0002**	0.0008***	0.0028***	0.0012**
MEX	0.0003**	0.0004**	0.0009**	0.0165***
NIC	0.0002**	0.0002**	0.0007**	0.0105***
PAN	0.0001*	0.0004**	0.0006**	0.0046**
PRY	0.0003**	0.0004**	0.0017**	0.0116***
PER	0.0006***	0.0005**	0.0010**	0.0116***
PHL	0.0003**	0.0004**	0.0010**	0.0083***
ROM	0.0006**	0.0010***	0.0019**	0.0025**
SGP	0.0003**	0.0006***	0.0015**	0.0073***
ZAF	0.0004**	0.0008***	0.0032***	0.0041***
SYR	0.0004***	0.0004**	0.0012**	0.0021**
THA	0.0004**	0.0006***	0.0010**	0.0053***
TTO	0.0003**	0.0003**	0.0036***	0.0165***
TUN	0.0003**	0.0003**	0.0006**	0.0011**
TUR	0.0006***	0.0007***	0.0018***	0.0029***
UGA	0.0003**	0.0002**	0.0036***	0.0017**
URY	0.0004**	0.0008***	0.0020***	0.0070***
VEN	0.0003**	0.0004**	0.0011**	0.0119***

Notes: *, ** and *** represent a level of significance of 10%, 5% and 1% respectively.