International R&D spillovers in the multi-country Schumpeterian growth model*

Cem Ertur[†] Wilfried Koch[‡]

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Abstract

This paper reconsiders the multi-country Schumpeterian growth model and its empirical implications. We first show that the model implies a spatial econometric reduced form. Indeed, the 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 model we propose includes the neoclassical growth model as a particular case. We can therefore test explicitly the role of R&D investment in the long run growth process against the Solow growth model which is nested in the Schumpeterian growth model. Finally, the proprieties 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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†LEO, Université d'Orléans, France. E-mail: cem.ertur@univ-orleans.fr

‡LEG, Université de Bourgogne, France. E-mail: kochwilfriedfr@aol.com, corresponding author.

1 Introduction

Empirical growth papers generally derive econometric reduced forms from the neoclassical growth model (Mankiw *et al.*, 1992), since it has some appropriate properties which allow 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) and are therefore perfectly technologically interdependent.

The propriety that economies have parallel long run growth paths is not shared by endogenous growth models implying two main problems. First, as also underlined by Howitt (2000), cross-country empirical evidence on income differences has been used to cast some doubt on endogenous growth models. 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. 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. Similarly, it is often argued that empirical evidence in favor of conditional $\beta-$convergence based on cross-country growth regressions is consistent with the neoclassical theory but not with the endogenous growth theory. Second it is difficult to estimate endogenous growth models 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 implying that steady-state growth rates are specific to each country and should be simultaneously estimated from the econometric point of view. In the neoclassical framework, this variable is exogenous and identical for each country and is generally assumed equal to 2%. Different authors, like Dinopoulos and Thomson (1996, 2002) for instance, propose to use simultaneous non-linear systems of equations to estimate Romer-Jones type of models (Romer, 1990; Jones, 1995a), 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 as 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, we take as a starting point 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.

One of the main contributions of this paper is to explicitly augment the research productivity function of endogenous growth models by adding a general process of technological interdependence as 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. 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).[1] 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 multi-country Schumpeterian growth model that we propose has some interesting proprieties which have not been previously studied in the literature. First, the econometric reduced form we obtain must be estimated using the appropriate spatial econometric methods as proposed in Ertur and Koch (2007). Second, the Solow growth model (Solow, 1956) is nested in our multi-country Schumpeterian growth model. Actually, when the R&D expenditures have no effect on the Poisson arrival process and on the growth rate of technology, our multi-country Schumpterian growth model reduces to the Solow growth model. From the econometric point of view, the Spatial Durbin Model (SDM) implied by our multi-country Schumpterian growth model reduces then to the Spatial Error Model (SEM). The implied non linear constraints may be easily tested. Finally, because of the implicit structure implied by our spatial econometric specification, the impact of the variation of an exogenous variable in a country affects all the countries in the sample. This property allows therefore to explicitly evaluate the impact of home and foreign R&D spillovers in our framework along the lines of Coe and Helpman (1995) or Coe *et al.* (1997). Indeed, our theoretical model implies that the level of per worker income at steady state for a given country depends on its own R&D expenditures rates but also on the R&D expenditures of foreign countries.

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

2.1 Hypotheses

Production relations 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

[1]See Aghion and Howitt (1998) p. 421 and footnote 23.

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 lasted 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, chapter 12) 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 (1995a,b) 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 proprieties 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 $\widetilde{\pi}_i \equiv \alpha(1-\alpha)\hat{k}_i(t)^{\alpha}$.

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 $\lambda_i > 0$ 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. We deflate R&D expenditures ($S_{i,A}(t)$) 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:

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

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, chapter 12, 1999) and Howitt (1999, 2000) assume that $A_i(t)^{max}$ grows at a rate proportionate 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:

$$g_i(t) \equiv \frac{\dot{A}_i(t)^{max}}{A_i(t)^{max}} = \frac{\sigma}{Q_i(t)} Q_i(t)\lambda_i\kappa_i(t)^{\phi} = \sigma\lambda_i\kappa_i(t)^{\phi} \tag{10}$$

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:

$$\frac{dA_i(t)}{dt} = \lambda_i\kappa_i(t)^{\phi}(A_i(t)^{max} - A_i(t)) \tag{11}$$

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 (10).

2.3 Physical capital accumulation

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

$$\dot{\hat{k}}_i(t) = s_{K,i}\hat{k}_i(t)^{\alpha} - (n_i + g_i(t) + \delta)\hat{k}_i(t) \tag{12}$$

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

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

In endogenous growth models, the change in knowledge is equal to the resources devoted to discover new ideas multiplied by the rate at which R&D generates new ideas denoted by λ_i. In order to introduce technological diffusion in the Schumpeterian growth model, we assume that this productivity parameter is defined as follows:

$$\lambda_i = \lambda \prod_{j=1}^{n} \left(\frac{A_j(t)}{A_i(t)} \right)^{\gamma_i w_{ij}} \tag{13}$$

We therefore suppose that R&D productivity is a negative function of the technological gap of country i with respect to its own technology frontier. This technological frontier is defined as the geometric mean of world knowledge levels denoted by $A_j(t)$, for $j = 1, ..., n$. This technological frontier is specific to each country because of w_{ij} parameters, which model the specific access of the country i to the accumulated knowledge of the country j. The general specification proposed in this paper[2] encompasses particular cases generally found in the literature like the world technological leader (Benhabib and Spiegel, 1994, 2005; or Nelson and Phelps, 1966). We discuss on the particular structure of the obtained **W** matrix below. We assume that $\sum_{j=1}^{n} w_{ij} = 1$. The parameter $\gamma_i > 1$ measures the absorption capacity of country i which we assume as a function of its human capital stock as: $\gamma_i = \gamma H_i$, with $\gamma < 1$. Introducing equation (13) into the growth rate of the average accumulated knowledge in country i, we have:

$$g_i \equiv \frac{\dot{A}_i(t)}{A_i(t)} = \lambda \sigma \kappa_i(t)^{\phi} \prod_{j=1}^{n} \left(\frac{A_j(t)}{A_i(t)} \right)^{\gamma_i w_{ij}} \tag{14}$$

The idea developed here is very simple. We assume that each country has a technology frontier defined in the third term of equation (14). This is the gap with respect to this technology frontier which determines the research productivity of a country. Indeed, the farther away a country is from its own technology frontier the higher is its productivity in the research sector because it can beneficiates 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 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 technology frontier the more it beneficiates from foreign technology to innovate and the higher is its research productivity. The distance with respect to countries'

[2] Aghion and Howitt (1998) and Ertur and Koch (2007) propose similar specification of the world technological frontier.

own technology 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, 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]

$$g_w = \lambda \sigma \kappa_i^\phi \prod_{j=1}^{n} \left(\frac{A_j}{A_i} \right)^{\gamma_i w_{ij}} \quad \text{for} \quad i = 1, ..., n \tag{15}$$

Each country has the same steady state growth rate because of inverse relation between the resources devoted to 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 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 to its 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.

Aghion and Howitt (1998) specify a very close function and assume that each country has the same technology frontier since each country diffuses the same quantity of knowledge to all other foreign countries, that is: $w_{ij} = w_j$ for each country. For this reason, as we will show, the interdependence pattern can be thrown in the constant term of their empirical specification, thus preventing full exploitation of some fundamental theoretical and econometric implications of their model. In our model, we generalize this approach by assuming a richer structure of interdependence between countries. Moreover, as we will discuss below, we use the fact that the interaction matrix with general term w_{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: $w_{ii} \equiv \frac{\gamma_i - 1}{\gamma_i} < 1$, for $i = 1, ..., n$, we have:

$$g_w = \frac{\sigma \lambda}{((1+\sigma)\xi)^\phi} s_{A,i}^\phi y_i^\phi n_i^\phi A_i^{-\phi-1} \prod_{j \neq i}^{n} A_j^{\gamma_i w_{ij}} \tag{16}$$

Taking logarithms of equation (16), we rewrite the obtained equation as:

$$\ln A_i = \frac{1}{1+\phi} \ln \frac{\sigma \lambda}{g_w((1+\sigma)\xi)^\phi} + \frac{\phi}{1+\phi} (\ln s_{i,A} + \ln n_i + \ln y_i) + \frac{\gamma H_i}{1+\phi} \sum_{j \neq i}^{n} w_{ij} \ln A_j \tag{17}$$

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 im-

[3]At this step, all variables are defined at steady state, we therefore drop the time reference without lost generality.

plies 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 $w_{ij} = w_j$ for $j = 1, ..., n$ and $\gamma_i = \gamma$ for $i = 1, ..., n$, Aghion and Howitt (1998) consider the last term of equation (17) as a constant and therefore they cannot fully take into account the interdependence underlying the multi-country Schumpeterian growth model as well as some interesting predictions associated to their theoretical model. In contrast, we propose a richer interdependence scheme, using the modeling strategy elaborated by Ertur and Koch (2007). For this, rewrite equation (17) in matrix form to obtain:

$$\mathbf{A} = \frac{1}{1+\phi} \ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}} \mathbb{1}_{(\mathbf{n},\mathbf{1})} + \frac{\phi}{1+\phi}(\mathbf{s_A} + \mathbf{y} + \mathbf{n}) + \frac{\gamma}{1+\phi}\mathbf{WA} \tag{18}$$

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, $\mathbf{W}$ the $(n \times n)$ matrix of interaction terms premultiplied by the $(n \times n)$ diagonal matrix of human capital stocks. We can resolve this equation for $\mathbf{A}$, if $\frac{\gamma}{1+\phi} \neq 0$ and if $\frac{1+\phi}{\gamma}$ is not an eigenvalue of $\mathbf{W}$:[4]

$$\begin{aligned} \mathbf{A} &= \frac{1}{1+\phi}\left(\mathbf{I} - \frac{\gamma}{1+\phi}\mathbf{W}\right)^{-1}\left(\ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}} \mathbb{1}_{(\mathbf{n},\mathbf{1})}\right) \\ &+ \frac{\phi}{1+\phi}\left(\mathbf{I} - \frac{\gamma}{1+\phi}\mathbf{W}\right)^{-1}(\mathbf{s_A} + \mathbf{y} + \mathbf{n}) \end{aligned} \tag{19}$$

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

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 (19) in the production function and rearranging terms, we obtain:

$$\mathbf{y} = \left(\ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}}\right)\mathbb{1}_{(\mathbf{n},\mathbf{1})} + \phi(\mathbf{s_A} + \mathbf{n}) + \frac{\alpha(1+\phi)}{1-\alpha}\mathbf{S_K} - \frac{\alpha\gamma}{1-\alpha}\mathbf{WS_K} + \gamma\mathbf{Wy} \tag{20}$$

[4] Actually $\left(\mathbf{I} - \frac{\gamma}{1+\phi}\mathbf{W}\right)^{-1}$ exists if and only if $\left|\mathbf{I} - \frac{\gamma}{1+\phi}\mathbf{W}\right| \neq 0$. This condition is equivalent to: $\left|\frac{\gamma}{1+\phi}\right| \left|\mathbf{W} - \frac{1+\phi}{\gamma}\mathbf{I}\right| \neq 0$ where $\left|\frac{\gamma}{1+\phi}\right| \neq 0$ and $\left|\mathbf{W} - \frac{1+\phi}{\gamma}\mathbf{I}\right| \neq 0$.

or for a country i:

$$\begin{aligned}\ln y_i &= \ln \frac{\sigma\lambda}{g_w((1+\sigma)\xi)^{\phi}} + \phi(\ln s_{A,i} + \ln n_i) + \frac{\alpha(1+\phi)}{1-\alpha} \ln \frac{s_{K,i}}{n_i + g_w + \delta} \\ &- \frac{\alpha\gamma H_i}{1-\alpha} \sum_{j\neq i}^{n} w_{ij} \ln \frac{s_{K,j}}{n_j + g_w + \delta} + \gamma H_i \sum_{j\neq i}^{n} w_{ij} \ln y_j \end{aligned} \tag{21}$$

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 value of per worker income.[5]

Proposition 1 (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:*

$$\Xi_i^{s_{K,i}} = \frac{\alpha(1+\phi)}{1-\alpha} + \frac{\alpha\phi}{1-\alpha} \sum_{r=1}^{\infty} \gamma_i^r w_{ii}^{(r)} > 0 \tag{22}$$

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

$$\Xi_i^{s_{K,j}} = \frac{\alpha\phi}{1-\alpha} \sum_{r=1}^{\infty} \gamma_i^r w_{ij}^{(r)} > 0 \quad \textit{for} \quad j = 1, ..., n, \quad j \neq i \tag{23}$$

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 the 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 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 home country i or in the foreign country j, $s_{K,j}$ for $j = 1, ..., n$,

[5] See Appendix for the proof.

increases the per worker income of the country i because of the spatial 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 investment rate $s_{K,i}$ is higher because of spatial 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 2 (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:*

$$\Xi_i^{n_i} = -\frac{\alpha}{1-\alpha}\left(\frac{n_i}{n_i + g_w + \delta}\right) + \frac{\alpha\phi}{1-\alpha}\left(\frac{g_w + \delta}{n_i + g_w + \delta}\right)\left(1 + \sum_{r=1}^{\infty}\gamma_i^r w_{ii}^{(r)}\right) \tag{24}$$

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

$$\Xi_i^{n_j} = \frac{\alpha\phi}{1-\alpha}\left(\frac{g_w + \delta}{n_j + g_w + \delta}\right)\sum_{r=1}^{\infty}\gamma_i^r w_{ij}^{(r)} > 0 \quad for \quad j = 1, ..., n, \quad j \neq i \tag{25}$$

As previously, we first 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: $\phi\frac{g_w+\delta}{n_i}\left(1 + \sum_{r=1}^{\infty}\gamma_i^r w_{ii}^{(r)}\right) > 1$. 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. Finally, 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 the country i beneficiates more from foreign technology throughout parameters w_{ij} and human capital H_i.

Proposition 3 (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:*

$$\Xi_i^{s_{A,i}} = \phi + \phi \sum_{r=1}^{\infty} \gamma_i^r w_{ii}^{(r)} > 0 \tag{26}$$

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

$$\Xi_i^{s_{A,j}} = \phi \sum_{r=1}^{\infty} \gamma_i^r w_{ij}^{(r)} > 0 \tag{27}$$

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 convergent with the empirical results implied by the Coe and Helpman (1995) model and subsequent studies. An 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 convergent with these empirical results. We quantify the implied international R&D diffusion effect in Section 7.

5 Econometric specification

Using equation (21), 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:

$$\ln y_i = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \beta_2 \ln s_{i,A} + \beta_3 \ln n_i + \theta H_i \sum_{j \neq i}^{n} w_{ij} \ln \frac{s_{K,j}}{n_j + 0.05} + \gamma H_i \sum_{j \neq i}^{n} w_{ij} \ln y_j + \varepsilon_i \tag{28}$$

with: β_0, the constant identical for each country, $\beta_1 = \frac{\alpha(1+\phi)}{1-\alpha} > 0$ the coefficients associated with the investment rate in physical capital and the effective depreciation rate of the home country i respectively, $\beta_2 = \beta_3 = \phi > 0$ the coefficient associated with the investment rate in the R&D sector, $\theta = -\frac{\alpha\gamma}{1-\alpha} < 0$ the coefficients associated with the investment rate in physical capital and the effective depreciation rate of the foreign country j, for $j = 1, ..., n$, $j \neq i$, respectively and $\gamma > 0$ the spatial autocorrelation coefficient. Finally, the error terms ε_i, for $i = 1, ..., n$, are assumed identically and independently distributed. In matrix form, we obtain a Spatial Durbin Model:

$$\mathbf{y} = \mathbf{X}\beta + \mathbf{WZ}\theta + \rho\mathbf{Wy} + \varepsilon \tag{29}$$

where $\mathbf{y}$ is the $(n \times 1)$ vector of per worker income levels; $\mathbf{X}$ is the $(n \times 4)$ matrix with the exogenous variables: the constant, the logarithms of the investment rates in physical capital divided by the effective depreciation rates, the logarithms of worker growth rate and the logarithms of expenditures in the research sector; $\mathbf{Z}$ is the $(n \times 1)$ matrix with the spatial lag of the logarithms of the investment rates in physical capital divided the effective depreciation rates; $\mathbf{W}$ is the $(n \times n)$ spatial weight matrix. β is the (4×1) coefficients vector associated with the exogenous variables and γ is the spatial autocorrelation parameter. ε is the $(n \times 1)$ vector of error terms assumed identically and independently distributed with mean zero and variance $\sigma^2 \mathbf{I_n}$.

We note that, since this model is a model including both the Schumpeterian growth model of Aghion and Howitt (1992) and the neoclassical 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 that of 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 the following econometric reduced form:

$$\ln y_i = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \theta H_i \sum_{j \neq i}^{n} w_{ij} \ln \frac{s_{K,j}}{n_j + 0.05} + \gamma H_i \sum_{j \neq i}^{n} w_{ij} \ln y_j + \varepsilon_i \tag{30}$$

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 $j = 1, ..., n$, respectively and $\gamma > 0$ the spatial autocorrelation coefficient. Finally, the error terms ε_i, for $i = 1, ..., n$, are assumed identically and independently distributed. We therefore have the following constraint between parameters: $\beta\gamma = -\theta$. The model is the constrained form of the Spatial Durbin Model (SDM) which is equivalent to the Spatial Error Model (SEM). We have in matrix form:

$$\begin{aligned} \mathbf{y} &= \mathbf{X}\beta + \varepsilon_{\mathbf{Solow}} \\ \varepsilon_{\mathbf{Solow}} &= \rho \mathbf{W} \varepsilon_{\mathbf{Solow}} + \varepsilon \end{aligned} \tag{31}$$

It is therefore possible to test endogenous technical progress implied by the Schumpeterian growth model against the neoclassical exogenous technological progress using the non linear constraint.

We note that, if we constrained the coefficient α to some appropriate value (we take one third), we obtain the following econometric reduced form:

$$\ln TFP_i = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \beta_2 \ln s_{A,i} + \beta_3 \ln n_i + \gamma H_i \sum_{j \neq i}^{n} w_{ij} \ln TFP_j \tag{32}$$

where: $\ln TFP_i = \ln y_i - 0.05 \ln \frac{s_{K,i}}{n_i + 0.05}$ 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 population growth rate respectively. γ is the spatial autocorrelation parameter. In matrix form, the model is written as follows:

$$\mathbf{y} = \mathbf{X}\beta + \rho\mathbf{W}\mathbf{y} + \varepsilon \tag{33}$$

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 or in other words the impact of R&D expenditures and the impact of foreign accumulated knowledge representing technological interdependence.

Finally, 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 (26) and (27). We therefore obtain the estimated matrix of elasticities, using the coefficients of the econometric reduced form:

$$\widehat{\boldsymbol{\Xi}}^{\mathbf{sA}}_{\mathbf{TFP}} = \hat{\beta}_2 \left(\mathbf{I} - \hat{\gamma}\mathbf{W}\right)^{-1} \tag{34}$$

and the Delta method can be used to assess statistical significance of these elasticities.

6 Data and spatial weight matrices

6.1 Data

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 $g_w + \delta = 0.05$.

The matrix $\mathbf{W}$ corresponds to the so-called spatial weight matrix commonly used in spatial econometrics to model spatial interdependence between regions or countries (Anselin 2006). More precisely, each country is connected to a set of neighboring countries by means of an exogenous pattern introduced in $\mathbf{W}$. Elements on the main diagonal are set to zero by convention whereas elements w_{ij} indicate the way country i is connected to country j.

We use two spatial weight matrices in order to relate our results to those obtained in the literature. We therefore consider for the first matrix, a pure geographical distance, more precisely great-circle distance between capitals. Geographical distance has also been considered among others by Eaton and Kortum (1996), Klenow and Rodriguez-Clare (2005), Moreno and Trehan (1997) and Ertur and Koch (2007).[6] The functional forms we consider is simply the negative exponential of distance as suggested by Keller (2002). The general terms of this matrix $\mathbf{W1}$ is defined as follows $H_i w1_{ij} = H_i w1^*_{ij} / \sum_j w1^*_{ij}$ where:

$$w1^*_{ij} = \begin{cases} 0 \ \text{ if } \quad i = j \\ e^{-d_{ij}} \quad \text{otherwise} \end{cases} \tag{35}$$

with d_{ij} is the great-circle distance between country capitals and H_i the human capital stock of destination country.

The second matrix we consider, $\mathbf{W2}$, is a matrix of trade flows, as suggested by Grossman and Helpman (1991), Coe and Helpman (1995) and Coe *et al.* (1997) among others. The general terms of this matrix $\mathbf{W2}$ is defined as follows in standardized form $H_i w2_{ij} = H_i w2^*_{ij} / \sum_j w2^*_{ij}$ where:

$$w2^*_{ij} = \begin{cases} 0 \ \text{ if } \quad i = j \\ m_{ij} \quad \text{otherwise} \end{cases} \tag{36}$$

with m_{ij} the average fraction of country j's imports coming from country i over the 1990-2000 period. 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 Soto and Cohen (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

[6] Klenow and Rodriguez-Clare (2005, p. 28-29) suggest that use of pure geographical distance could capture trade and FDI related spillovers.

censuses obtained directly from national statistical agencies web pages.[7]

6.2 General interdependence patterns

Let us consider some possible interdependence patterns between countries incorporated in the spatial weight matrix $\mathbf{W}$. In order to visualize them, let us consider 5 interdependent countries. This is the more complete structure of interdependence between countries that it is possible to consider. In order to use analytically this complete structure of interdependence, we represent it in the following (5×5) matrix:

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

The flow 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 representing the emitting country. When countries are regrouped in clubs, the $\mathbf{W}$ matrix has a particular structure. Assume that the first to the third countries belong to the first club and the two last countries belong to the second club. The $\mathbf{W}$ matrix has then a bloc structure.

The successive powers of the $\mathbf{W}$ matrix give the knowledge diffusion pattern between countries. 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 of knowledge. Second, the sub-matrix $\mathbf{W_{12}}$ represents the diffusion of knowledge from countries in the club 2 to the countries in the club 1, whereas the sub-matrix $\mathbf{W_{21}}$ represents the diffusion of knowledge from countries in the club 1 to the countries in the club 2. The technological multiplier effect is modeled by:[8]

$$(\mathbf{I} - \gamma \mathbf{W})^{-1} = \mathbf{I} + \gamma \mathbf{W} + \gamma^2 \mathbf{W^2} + ... + \gamma^r \mathbf{W^r} + ... = \sum_{r=0}^{\infty} \gamma^r \mathbf{W^r} \quad (37)$$

Therefore, the technological multiplier effect is represented by the successive powers of the matrix. Let us 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

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

[8] It is defined when $|\gamma|$ is less than the reciprocal of the largest eigenvalue of $\mathbf{W}$.

the technological leader and countries 1, 2, 3 and 4 are technological followers. The matrix of interactions can be defined as follows:

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

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

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

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 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. We consider that the North club can diffuse 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:

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

We note that these terms are 0 for the relations from club 1 (the South club) to the 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 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 analyzed carefully. Using the inverse of partitioned matrix, we obtain easily:

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

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:

$$\gamma \sum_{r=0}^{\infty}\sum_{s=0}^{\infty} \gamma^r \gamma^s \mathbf{W_{11}^r W_{12} W_{22}^s} \tag{38}$$

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 $\gamma^2(\mathbf{W_{12}W_{22}}+\mathbf{W_{11}W_{12}})$ which corresponds to one type of the indirect diffusion of knowledge. The first part of this expression, that is $\gamma^2\mathbf{W_{12}W_{22}}$, represents the diffusion inside the North club ($\mathbf{W_{22}}$) retransmitted in 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 others 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 interdependence 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). We propose here a generalization which allows considering any type of direct and indirect diffusion. To our knowledge, only Lumenga-Neso *et al.* (2005) have recently suggested a similar approach. However, our approach derives structurally from the multi-country Schumpeterian growth model and requires use of the appropriate spatial econometric estimation methods.

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 when R&D expenditures have no effect on growth and development ($\phi = 0$) and when there is no technological interdependence between countries ($\gamma = 0$). 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 Least Squares estimation. Our results for its qualitative predictions are essentially identical to those of Mankiw *et al.* (1992), since the coefficient on investment rate divided by working-age population growth 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 from the multi-country Schumpeterian growth model as proposed by Aghion and Howitt (1998) or Howitt (2000). They consider 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 (21), can be thrown in the constant term since it is identical for each country. In other words, the technology frontier is viewed as identical for each country. Rewrite equation (28) omitting the spatial lags of endogenous and exogenous variables as proposed by these authors, we have:

$$\ln y_i(t) = \beta_0 + \beta_1 \ln \frac{s_{K,i}}{n_i + 0.05} + \beta_2 \ln s_{A,i} + \beta_3 \ln n_i + \varepsilon_{AH,i} \tag{39}$$

where β_0 is the identical constant for all countries; $\beta_1 = \frac{\alpha(1+\phi)}{1-\alpha} > 0$ is the coefficient of 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 the second column of Table 1, we estimate 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 but the coefficient associated with the working-age population growth rate, reflecting the effect of horizontal differentiation, is not significant.

Multi-country Schumpeterian growth model v.s. Multi-country Solow growth model The Solow growth model, the Ertur and Koch (2007) and the Aghion and Howitt (1998) or Howitt (2000) models are particular cases of our multi-country Schumpeterian growth model. In fact the Solow growth model omits R&D expenditures variables and technological interdependence implying biased estimation. We can indeed rewrite the error terms of the textbook Solow growth model as follows:

$$\varepsilon_{\mathbf{Solow}} = \phi \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \mathbf{S_A} + \frac{\alpha\phi}{1-\alpha} \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \mathbf{S_K} + \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \varepsilon \tag{40}$$

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 terms of Aghion and Howitt (1998) and Howitt (2000) econometric reduced form can be also be rewritten as follows:

$$\varepsilon_{\mathbf{AH}} = \phi \sum_{r=1}^{\infty} \gamma^r \mathbf{W}^r \mathbf{S_A} + \frac{\alpha\phi}{1-\alpha} \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \mathbf{S_K} + \left(\mathbf{I} - \gamma \mathbf{W}\right)^{-1} \varepsilon \tag{41}$$

Therefore, although the econometric reduced form of Aghion and Howitt (1998) and Howitt (2000) contains the 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 implying the important propriety of international R&D spillover 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 the econometric model often found in the literature based on the multi-country Schumpeterian growth model is clearly misspecified and is estimated without using appropriate estimation methods.

We therefore need to take into account technological interdependence between countries. To this end, we estimate our multi-country Solow growth model in the two subsequent columns of Table 1.[9] The results are qualitatively equivalent to those of the Solow growth model when we estimate the Spatial Error Model (SEM) implied by our theoretical model. Indeed, the coefficients have the expected signs and remain highly significant. Moreover, the coefficient γ measuring the degree of technological interdependence between countries, and therefore the coefficient of spatial autocorrelation in the SEM, is high and significant. Countries cannot be considered as independent observations and statistical inference is plagued by the presence of spatial autocorrelation in the error terms (see Anselin, 2006).

In the columns 5 to 6 of Table 1, we estimate our multi-country Schumpeterian growth model, that is the specification (28), for the two spatial weight matrices. All parameters have

[9] We use the maximum likelihood estimator (see Anselin, 2006; Ertur and Koch, 2007). James LeSage provides Matlab routines for estimating the spatial Durbin model and the Spatial Error Model in his Econometrics Toolbox (`http://www.spatial-econometrics.com`).

the expected signs and are significant except the working-age population growth rate. We note that the coefficient investment rate in physical capital divided by the effective depreciation rate is close to 0.5-0.7 and remains highly significant. The coefficient associated with the R&D expenditure decreases to 0.19-0.23 and is highly significant. Finally, we note that the spatial autocorrelation parameter γ is close to 0.08-0.1 and is significant showing the importance of international knowledge spillovers in the growth and development processes. The estimated of γ, which measures absorbtion capacity of receiving country, is close to obtained values in Benhabib and Spiegel (1994, 2005). These results show clearly that the specification of Aghion and Howitt (1998) and Howitt (2000) does not capture all the rich interaction structure implied by the multi-country Schumpeterian growth model.

Finally, the common factor test shows that the restricted Spatial Durbin Model is strongly rejected in favor of the unrestricted one whatever the spatial weight matrix considered. These results first suggest, that the SEM is not the appropriate model to capture the spatial autocorrelation in the error terms. But more important, these results suggest that the R&D expenditures play an important role in growth and development processes which is consistent with our multi-country Schumpeterian growth model. In other words, the Solow growth model including technological interdependence is rejected in favor of the multi-country Schumpeterian growth model.

International diffusion of R&D We finally estimate the Total Factor Productivity equation implied by our multi-country Schumpeterian growth model using specification (32) 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 two spatial weight matrices. Only the coefficient of R&D expenditures remains significant in this specification, 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 note also that the spatial autocorrelation parameter is highly significant 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 allows to give some information about structural parameters. First, parameter $\beta_1 = \phi$, gives the value of the elasticity of Poisson arrival rate with respect to the productivity-adjusted expenditure on vertical R&D in each sector (ϕ). Its values range from about 0.14 for the **W1** matrix to 0.16 for the **W2** matrix. Finally, the spatial autocorrelation parameter, γ, gives the value of the elasticity of the productivity of vertical R&D with respect to the gap of the given country to its own technology frontier or the value of absorbtion capacity. The results show that the spatial autoregressive parameter is high and highly significant and therefore show the importance of international diffusion of knowledge. We use these results in order to quantify the international R&D spillovers implied by our multi-country Schumpeterian growth model.

Table 2 around here

Using the econometric results of Table 2, we quantify the impact of home and foreign R&D expenditures on 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 as: $\widehat{\boldsymbol{\Xi}}^{\mathbf{SA}}_{\mathbf{TFP}} = \widehat{\beta}_1 \left(\mathbf{I} - \widehat{\rho}\mathbf{W}\right)^{-1}$. We display all the results in Table 3. The Table is divided in two parts. The upper part displays intra OECD R&D spillovers and the bottom part, the North-South R&D spillovers (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 note finally 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, this effect differs in function of the particular relation between countries.

The United States is the country which diffuses the most its R&D to other countries. 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 others American countries, like Canada, Mexico, Costa Rica or Colombia for instance (Canada imports almost 48% from the United States in our sample, Mexico, 67%; Costa Rica, 56%; and Colombia, 35%). We also note the importance of human stock as absorption capacity in international R&D diffusion since the impact on Canada is more important than on Mexico although this last 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 of Japan-South East Asian countries are also higher than from the others Japan R&D diffusion. We also denote the high effect on South Korea because of the level of its human capital stock. 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 seem more appealing than to consider that all the countries have the same technological leader.

We note that knowledge diffuses locally between European countries where elasticities are higher for larger origin countries as United Kingdom, Germany or France than for other countries. Some particular relations imply that elasticities are high as for the UK-Ireland elasticity and Germany-Austria elasticity for instance. We also note that the elasticities European-African countries are relatively high showing the importance of European countries (essentially France and United-Kingdom) as a technological leader for African countries. We finally note the high bilateral impacts of Australia and New Zealand with respect to their Total Factor Productivity levels. These regional results are consistent with those of Coe *et al.* (1997) and show the heterogeneity of the international diffusion of knowledge.

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 pattern. Moreover, following the methodology developed by Ertur and Koch (2007), we show how multi-country growth models imply spatial econometric reduced forms. A structural test discriminating between endogenous growth model motivated by R&D expenditures and the Solow growth model is proposed. The implicit nature of the theoretical as well as the empirical model 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 show the importance of productivity differences along with physical capital accumulation. They also show how the neoclassical growth model is rejected in favor to the Schumpeterian growth theory.

This paper is based on the idea of parallel long run growth paths. Recent development of the Schumpeterian growth theory suggest to generalize our framework allowing non-parallel long run ways of growth (Howitt and Mayer-Foulkes, 2005; Acemoglu *et al.*, 2006) allowing richer structure of clubs. Our structural approach seems promising to structurally estimate and test theoretical predictions of these models.

Table 1: Multi-country Solow growth model v.s. Multi-country Schumpeterian growth model

Models	Solow	AH	Multi-country Solow		Multi-country Schumpeter	
Obs. / Weight matrix	59	59	59 / (**W1**)	59 / (**W2**)	59 / (**W1**)	59 / (**W2**)
constant	3.813	3.585	3.781	3.908	4.455	4.236
	(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	1.351	0.671	0.493
	(0.000)	(0.004)	(0.000)	(0.000)	(0.000)	(0.001)
$\ln s_{A,i}$	—	0.275	—	—	0.232	0.187
		(0.001)			(0.000)	(0.007)
$\ln n_i$	—	-0.811	—	—	0.219	0.158
		(0.382)			(0.801)	(0.860)
$\mathbf{W}(\ln s_{K,j} - \ln(n_j + 0.05))$	—	—	—	—	-0.314	-0.371
					(0.000)	(0.238)
γ	—	—	0.151	0.644	0.080	0.101
			(0.017)	(0.000)	(0.000)	(0.013)
LR test	—	—	—	—	39.717	44.422
					(0.000)	(0.000)
R^2 or Pseudo$-R^2$	0.541	0.706	0.541	0.541	0.787	0.757
$\bar{R}^2$	0.533	0.690	—	—	—	—
AIC	-0.417	-0.794	-0.491	-0.308	-1.063	-0.959
BIC	-0.346	-0.653	-0.421	-0.238	-0.887	-0.783

Notes: p-values are in parentheses. AIC is the Akaike information criterium. BIC is the Schwarz information criterium. Pseudo$-R^2$ is the squared correlation between predicted and actual values. LR is the likelihood ratio test for linear restrictions and the common factor test. OLS-White indicates the use of heteroscedasticity consistent covariance matrix estimator of White (1980) in OLS estimation.

Table 2: Total Factor Productivity equation

Obs. / Weight matrix	59 / (**W1**)	59 / (**W2**)
Unrestricted model		
constant	4.110	4.055
	(0.003)	(0.002)
$\ln s_{K,i} - \ln(n_i + 0.05)$	-0.038	-0.114
	(0.898)	(0.699)
$\ln n_i$	0.045	0.086
	(0.962)	(0.925)
$\ln s_{A,i}$	0.173	0.164
	(0.012)	(0.013)
γ	0.052	0.060
	(0.003)	(0.000)
Pseudo$-R^2$	0.603	0.613
AIC	-0.929	-0.974
BIC	-0.788	-0.834
Restricted model		
constant	4.212	4.077
	(0.000)	(0.000)
$\ln s_{A,i} + \ln n_i + \ln s_{K,i} - \ln(n_i + 0.05)$	0.158	0.145
	(0.013)	(0.015)
γ	0.050	0.056
	(0.002)	(0.000)
Test of restriction (LR)	0.449	0.792
	(0.930)	(0.851)
Pseudo$-R^2$	0.598	0.607
AIC	-0.989	-1.029
BIC	-0.919	-0.958

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

Appendix: Elasticities

To resolve equation (20) for $\mathbf{y}$, we subtract $\gamma\mathbf{W}\mathbf{y}$ from both sides and we premultiply both sides by $(\mathbf{I}-\gamma\mathbf{W})^{-1}$ to obtain:

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

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:

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

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:

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

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:

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

where $\mathbf{diag}\left(\frac{\mathbf{n}}{\mathbf{n}+\mathbf{g}+\delta}\right)$ and $\mathbf{diag}\left(\frac{\mathbf{g}+\delta}{\mathbf{n}+\mathbf{g}+\delta}\right)$ 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 $i=1,...,n$.

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Table 3: International R&D spillovers

	AUS	AUT	BEL	CAN	DNK	FIN	FRA	GER
AUS	**0.1640****	0.0003**	0.0007**	0.0011**	0.0003**	0.0004**	0.0018**	0.0039**
AUT	0.0001*	**0.1639****	0.0013**	0.0003**	0.0004**	0.0004**	0.0025**	0.0157***
BEL	0.0002**	0.0003**	**0.1642****	0.0003**	0.0003**	0.0003**	0.0054***	0.0075***
CAN	0.0006**	0.0003**	0.0006**	**0.1641****	0.0003**	0.0003**	0.0020**	0.0032**
DNK	0.0001**	0.0005**	0.0017**	0.0003**	**0.1639****	0.0012***	0.0027**	0.0091***
FIN	0.0003**	0.0006**	0.0014**	0.0004**	0.0015***	**0.1638****	0.0022**	0.0068***
FRA	0.0002**	0.0004**	0.0032***	0.0003**	0.0004**	0.0003**	**0.1644****	0.0070***
GER	0.0002**	0.0019***	0.0031***	0.0005**	0.0009***	0.0005***	0.0055***	**0.1653****
GRC	0.0001**	0.0005**	0.0014**	0.0002**	0.0005***	0.0004***	0.0032***	0.0061***
IRL	0.0001**	0.0002**	0.0008**	0.0004**	0.0004**	0.0003**	0.0020**	0.0032**
ITA	0.0002**	0.0009***	0.0020***	0.0004**	0.0004**	0.0003**	0.0051***	0.0074***
JPN	0.0030***	0.0003**	0.0007**	0.0021***	0.0004**	0.0002**	0.0019**	0.0036**
KOR	0.0020***	0.0002**	0.0004**	0.0011**	0.0002**	0.0002**	0.0012**	0.0028**
NLD	0.0002**	0.0005**	0.0045***	0.0004**	0.0005**	0.0005***	0.0033**	0.0087***
NZL	0.0090***	0.0002**	0.0005**	0.0009**	0.0003**	0.0003**	0.0012**	0.0027**
NOR	0.0002**	0.0005**	0.0013**	0.0009***	0.0028***	0.0014***	0.0022**	0.0063***
PRT	0.0001**	0.0002**	0.0010**	0.0001**	0.0002**	0.0002**	0.0030***	0.0040***
ESP	0.0001**	0.0004**	0.0014**	0.0002**	0.0003**	0.0003**	0.0057***	0.0056***
SWE	0.0002**	0.0006**	0.0017**	0.0003**	0.0028***	0.0022***	0.0027**	0.0078***
CHE	0.0001**	0.0017***	0.0018**	0.0003**	0.0005**	0.0004**	0.0050***	0.0132***
GBR	0.0004**	0.0004**	0.0022***	0.0007**	0.0007***	0.0006***	0.0042***	0.0066***
USA	0.0008***	0.0005**	0.0014**	0.0027***	0.0005**	0.0004**	0.0037***	0.0072***
ARG	0.0002**	0.0002**	0.0005**	0.0004**	0.0001**	0.0002**	0.0017**	0.0024**
BOL	0.0001*	0.0001**	0.0002**	0.0003**	0.0001**	0.0001**	0.0005**	0.0012**
BRA	0.0002**	0.0002**	0.0004**	0.0007***	0.0001**	0.0002**	0.0010**	0.0027**
BFA	0.0000**	0.0000**	0.0005**	0.0001**	0.0001***	0.0000*	0.0048***	0.0006**
CHL	0.0003**	0.0001**	0.0004**	0.0009***	0.0002**	0.0002**	0.0013**	0.0022**
CHN	0.0007***	0.0001**	0.0003**	0.0006**	0.0001**	0.0002***	0.0008**	0.0018**
COL	0.0001**	0.0001**	0.0003**	0.0008***	0.0001**	0.0001**	0.0009**	0.0017**
CRI	0.0001*	0.0001**	0.0002**	0.0004**	0.0001**	0.0001**	0.0008**	0.0012**
CUB	0.0001*	0.0001**	0.0005**	0.0019***	0.0001**	0.0001**	0.0020***	0.0011**
CYP	0.0001**	0.0002**	0.0007**	0.0002**	0.0003**	0.0002**	0.0016**	0.0037***
ECU	0.0002**	0.0001**	0.0004**	0.0006**	0.0001**	0.0001**	0.0007**	0.0017**
EGY	0.0002**	0.0002**	0.0005**	0.0002**	0.0002**	0.0002***	0.0018***	0.0024**
SLV	0.0001**	0.0001**	0.0002**	0.0003**	0.0001**	0.0001**	0.0009**	0.0012**
HND	0.0001*	0.0001*	0.0002**	0.0003**	0.0001**	0.0001**	0.0005**	0.0009**
HUN	0.0001*	0.0037***	0.0012**	0.0002**	0.0003**	0.0005***	0.0020**	0.0104***
IND	0.0007***	0.0001**	0.0015***	0.0003**	0.0001**	0.0001**	0.0007**	0.0019**
JAM	0.0002**	0.0001*	0.0003**	0.0009**	0.0002**	0.0001**	0.0009**	0.0012**
MDG	0.0001**	0.0001**	0.0006**	0.0001**	0.0001**	0.0000**	0.0063***	0.0010**
MYS	0.0008***	0.0001**	0.0003**	0.0003**	0.0001**	0.0001**	0.0008**	0.0016**
MUS	0.0008***	0.0001**	0.0007**	0.0001**	0.0001**	0.0001**	0.0048***	0.0017**
MEX	0.0002**	0.0001**	0.0003**	0.0008**	0.0001**	0.0001**	0.0008**	0.0020**
NIC	0.0001*	0.0001**	0.0002**	0.0004**	0.0002**	0.0001**	0.0006**	0.0009**
PAN	0.0003*	0.0000*	0.0002**	0.0003**	0.0001**	0.0001**	0.0005**	0.0009**
PRY	0.0001*	0.0000*	0.0001*	0.0002**	0.0000*	0.0000*	0.0005**	0.0009**
PER	0.0002**	0.0001**	0.0003**	0.0007**	0.0001**	0.0001**	0.0007**	0.0015**
PHL	0.0010***	0.0001**	0.0003**	0.0005**	0.0001**	0.0002**	0.0007**	0.0015**
ROM	0.0004***	0.0011***	0.0008**	0.0003**	0.0003**	0.0002**	0.0026**	0.0067***
SGP	0.0005**	0.0001**	0.0003**	0.0003**	0.0001**	0.0001**	0.0009**	0.0014**
ZAF	0.0005***	0.0002**	0.0007**	0.0003**	0.0002**	0.0002**	0.0013**	0.0041***
SYR	0.0001*	0.0003**	0.0009***	0.0001**	0.0001**	0.0001**	0.0019***	0.0027***
THA	0.0007**	0.0001**	0.0004**	0.0004**	0.0001**	0.0002**	0.0008**	0.0017**
TTO	0.0003**	0.0001**	0.0004**	0.0013***	0.0001**	0.0001**	0.0008**	0.0017**
TUN	0.0000*	0.0001**	0.0008**	0.0001**	0.0001**	0.0001**	0.0043***	0.0025***
TUR	0.0002**	0.0003**	0.0008**	0.0002**	0.0002**	0.0002***	0.0018**	0.0042***
UGA	0.0001**	0.0001**	0.0006**	0.0003**	0.0002***	0.0001**	0.0012***	0.0014**
URY	0.0001**	0.0001**	0.0003**	0.0002**	0.0001**	0.0001**	0.0014**	0.0014**
VEN	0.0001*	0.0001**	0.0004**	0.0008**	0.0001**	0.0001**	0.0008**	0.0016**

	GRC	IRL	ITA	JPN	KOR	NLD	NZL	NOR
AUS	0.0001**	0.0005**	0.0018**	0.0077***	0.0020**	0.0008**	0.0021***	0.0002**
AUT	0.0001**	0.0003**	0.0035***	0.0016**	0.0003**	0.0017**	0.0000**	0.0002**
BEL	0.0001**	0.0006**	0.0018**	0.0012**	0.0002**	0.0060***	0.0001**	0.0004**
CAN	0.0000**	0.0004**	0.0016**	0.0054***	0.0017**	0.0007**	0.0002**	0.0010***
DNK	0.0001**	0.0005**	0.0021**	0.0014**	0.0004**	0.0030***	0.0001**	0.0019***
FIN	0.0001***	0.0004**	0.0019**	0.0026***	0.0005**	0.0019**	0.0000**	0.0016***
FRA	0.0001**	0.0006***	0.0039***	0.0016**	0.0004**	0.0023***	0.0000**	0.0006***
GER	0.0002***	0.0008***	0.0041***	0.0027***	0.0006**	0.0044***	0.0001**	0.0009***
GRC	**0.1637****	0.0003**	0.0054***	0.0017***	0.0008***	0.0025***	0.0001**	0.0002**
IRL	0.0000**	**0.1639****	0.0011**	0.0023***	0.0006**	0.0015**	0.0000**	0.0006**
ITA	0.0003***	0.0004**	**0.1642****	0.0011**	0.0003**	0.0024***	0.0001**	0.0002**
JPN	0.0000**	0.0005**	0.0016**	**0.1645****	0.0034***	0.0007**	0.0005***	0.0003**
KOR	0.0000**	0.0003**	0.0011**	0.0101***	**0.1642****	0.0006**	0.0003**	0.0002**
NLD	0.0001**	0.0006**	0.0017**	0.0019**	0.0005**	**0.1643****	0.0000**	0.0009***
NZL	0.0000**	0.0003**	0.0013**	0.0061***	0.0011**	0.0007**	**0.1638****	0.0002**
NOR	0.0001**	0.0006**	0.0018**	0.0023***	0.0006**	0.0021**	0.0000**	**0.1639****
PRT	0.0000**	0.0002**	0.0022***	0.0008**	0.0002**	0.0014***	0.0000**	0.0003**
ESP	0.0001**	0.0004**	0.0033***	0.0014**	0.0004**	0.0016**	0.0000**	0.0003**
SWE	0.0001**	0.0006**	0.0018**	0.0017**	0.0004**	0.0027***	0.0000**	0.0028***
CHE	0.0001**	0.0006**	0.0044***	0.0017**	0.0004**	0.0024**	0.0000**	0.0003**
GBR	0.0001***	0.0016***	0.0025***	0.0025***	0.0006**	0.0032***	0.0002***	0.0012***
USA	0.0001**	0.0010***	0.0032***	0.0032***	0.0038***	0.0015**	0.0003***	0.0006**
ARG	0.0000**	0.0001**	0.0018***	0.0014**	0.0008**	0.0005**	0.0001**	0.0001**
BOL	0.0000**	0.0001**	0.0006**	0.0011**	0.0003**	0.0002**	0.0000**	0.0001**
BRA	0.0000**	0.0001**	0.0014***	0.0016***	0.0006**	0.0005**	0.0000**	0.0002**
BFA	0.0000**	0.0001**	0.0005**	0.0006***	0.0001**	0.0004**	0.0000*	0.0001**
CHL	0.0000**	0.0002**	0.0013**	0.0023***	0.0011**	0.0004**	0.0001**	0.0001**
CHN	0.0000**	0.0001*	0.0007**	0.0053***	0.0022***	0.0003**	0.0001**	0.0001**
COL	0.0000**	0.0001**	0.0008**	0.0018***	0.0005**	0.0003**	0.0000**	0.0001**
CRI	0.0000*	0.0002**	0.0006**	0.0013**	0.0008**	0.0003**	0.0000**	0.0001**
CUB	0.0000**	0.0001**	0.0015***	0.0006**	0.0001*	0.0006**	0.0002***	0.0001*
CYP	0.0023***	0.0003**	0.0026***	0.0023***	0.0015***	0.0008**	0.0000**	0.0004***
ECU	0.0000*	0.0001**	0.0011**	0.0023***	0.0006**	0.0004**	0.0000**	0.0001*
EGY	0.0001***	0.0003**	0.0019***	0.0012**	0.0006**	0.0006**	0.0001**	0.0001**
SLV	0.0000*	0.0001**	0.0005**	0.0011**	0.0007**	0.0003**	0.0001***	0.0001*
HND	0.0001***	0.0001*	0.0004**	0.0011**	0.0011**	0.0003**	0.0000**	0.0001*
HUN	0.0001**	0.0003**	0.0030***	0.0016**	0.0005**	0.0014**	0.0000*	0.0001**
IND	0.0000**	0.0001**	0.0007**	0.0016***	0.0006***	0.0005**	0.0001**	0.0001**
JAM	0.0000**	0.0002**	0.0007**	0.0014**	0.0007**	0.0006**	0.0001**	0.0004**
MDG	0.0000**	0.0001**	0.0006**	0.0010***	0.0003**	0.0003**	0.0000**	0.0000*
MYS	0.0000*	0.0002**	0.0005**	0.0064***	0.0014***	0.0004**	0.0002**	0.0001**
MUS	0.0000***	0.0002**	0.0010**	0.0015**	0.0005**	0.0003**	0.0003***	0.0001*
MEX	0.0000**	0.0002**	0.0007**	0.0017**	0.0008**	0.0003**	0.0001**	0.0001*
NIC	0.0000**	0.0001**	0.0005**	0.0019***	0.0009**	0.0003**	0.0000**	0.0001**
PAN	0.0001***	0.0001*	0.0011**	0.0111***	0.0036***	0.0002*	0.0001**	0.0002**
PRY	0.0000**	0.0001**	0.0006**	0.0012**	0.0007**	0.0002**	0.0000*	0.0000*
PER	0.0000**	0.0001**	0.0008**	0.0019***	0.0009**	0.0003**	0.0002***	0.0001**
PHL	0.0000**	0.0002**	0.0005**	0.0064***	0.0020***	0.0005**	0.0002**	0.0001*
ROM	0.0006***	0.0002**	0.0051***	0.0007**	0.0009***	0.0012**	0.0000**	0.0001**
SGP	0.0000**	0.0001**	0.0006**	0.0053***	0.0011**	0.0004**	0.0001**	0.0001**
ZAF	0.0000**	0.0003**	0.0012**	0.0024***	0.0006**	0.0008**	0.0001**	0.0001**
SYR	0.0002***	0.0001**	0.0024***	0.0015***	0.0012***	0.0007**	0.0000**	0.0001**
THA	0.0000**	0.0001**	0.0006**	0.0072***	0.0012**	0.0004**	0.0001**	0.0001**
TTO	0.0000*	0.0003**	0.0008**	0.0016**	0.0007**	0.0005**	0.0002***	0.0001*
TUN	0.0001***	0.0001**	0.0030***	0.0005**	0.0001**	0.0006**	0.0000**	0.0001**
TUR	0.0002***	0.0002**	0.0022***	0.0012**	0.0006**	0.0009**	0.0001**	0.0001**
UGA	0.0000**	0.0002**	0.0009***	0.0017***	0.0003**	0.0005**	0.0000**	0.0002**
URY	0.0000**	0.0001**	0.0016***	0.0010**	0.0007**	0.0003**	0.0000**	0.0001*
VEN	0.0000*	0.0001**	0.0012**	0.0013**	0.0005**	0.0004**	0.0001***	0.0001**

	PRT	ESP	SWE	CHE	GBR	USA
AUS	0.0001**	0.0004**	0.0010***	0.0008**	0.0035***	0.0116***
AUT	0.0003**	0.0007**	0.0007**	0.0016***	0.0016**	0.0024**
BEL	0.0002**	0.0008**	0.0009***	0.0006**	0.0034***	0.0027**
CAN	0.0001**	0.0004**	0.0007**	0.0006**	0.0032**	0.0164***
DNK	0.0004***	0.0007**	0.0045***	0.0008**	0.0034***	0.0025**
FIN	0.0004***	0.0007**	0.0045***	0.0008**	0.0035***	0.0035**
FRA	0.0004***	0.0023***	0.0007**	0.0010***	0.0033***	0.0036***
GER	0.0005***	0.0016***	0.0011***	0.0020***	0.0036***	0.0042**
GRC	0.0002**	0.0012***	0.0007**	0.0007**	0.0024***	0.0019**
IRL	0.0002**	0.0005**	0.0006**	0.0004**	0.0117***	0.0059***
ITA	0.0002**	0.0015***	0.0006**	0.0016***	0.0025***	0.0023**
JPN	0.0001**	0.0004**	0.0006**	0.0009**	0.0020**	0.0146***
KOR	0.0000*	0.0003**	0.0004**	0.0007**	0.0014**	0.0107***
NLD	0.0003**	0.0010**	0.0011***	0.0007**	0.0041***	0.0042***
NZL	0.0001**	0.0003**	0.0008**	0.0006**	0.0027**	0.0083***
NOR	0.0004***	0.0008**	0.0060***	0.0007**	0.0041***	0.0035**
PRT	**0.1638****	0.0048***	0.0004**	0.0004**	0.0019***	0.0011**
ESP	0.0009***	**0.1639****	0.0006**	0.0006**	0.0028***	0.0026**
SWE	0.0004***	0.0007**	**0.1641****	0.0009**	0.0040***	0.0033**
CHE	0.0003**	0.0009**	0.0008**	**0.1640****	0.0030**	0.0035**
GBR	0.0004***	0.0013***	0.0012***	0.0014***	**0.1644****	0.0057***
USA	0.0002**	0.0009**	0.0012***	0.0014***	0.0050***	**0.1651****
ARG	0.0001**	0.0011***	0.0004**	0.0004**	0.0009**	0.0062***
BOL	0.0000**	0.0005**	0.0004**	0.0002**	0.0004**	0.0040***
BRA	0.0001**	0.0005**	0.0004**	0.0005**	0.0009**	0.0059***
BFA	0.0000**	0.0003**	0.0001*	0.0001*	0.0004**	0.0008**
CHL	0.0001**	0.0010***	0.0006**	0.0004**	0.0009**	0.0074***
CHN	0.0000*	0.0002**	0.0003**	0.0003**	0.0007**	0.0036**
COL	0.0000**	0.0005***	0.0003**	0.0004**	0.0008**	0.0073***
CRI	0.0000**	0.0004**	0.0002**	0.0002**	0.0007**	0.0111***
CUB	0.0001**	0.0041***	0.0002**	0.0002**	0.0006**	0.0008*
CYP	0.0001**	0.0008***	0.0004**	0.0004**	0.0030***	0.0019**
ECU	0.0000**	0.0008***	0.0002**	0.0004**	0.0006**	0.0079***
EGY	0.0000**	0.0005**	0.0004**	0.0004**	0.0011**	0.0041***
SLV	0.0000**	0.0003**	0.0002**	0.0002**	0.0005**	0.0091***
HND	0.0000*	0.0004**	0.0001**	0.0003**	0.0006**	0.0124***
HUN	0.0001**	0.0006**	0.0007**	0.0010**	0.0016**	0.0019**
IND	0.0000**	0.0002**	0.0002**	0.0009***	0.0015***	0.0025***
JAM	0.0000*	0.0008***	0.0002**	0.0003**	0.0014**	0.0135***
MDG	0.0000**	0.0003**	0.0001**	0.0002**	0.0005**	0.0011**
MYS	0.0000**	0.0001**	0.0003**	0.0005**	0.0010**	0.0051***
MUS	0.0001**	0.0003**	0.0001**	0.0005**	0.0017***	0.0009**
MEX	0.0000*	0.0004**	0.0003**	0.0003**	0.0008**	0.0147***
NIC	0.0000**	0.0007***	0.0002**	0.0002**	0.0005**	0.0075***
PAN	0.0000**	0.0003**	0.0001*	0.0004**	0.0005**	0.0038**
PRY	0.0000**	0.0003**	0.0001**	0.0002**	0.0007**	0.0050***
PER	0.0000*	0.0007***	0.0004**	0.0003**	0.0006**	0.0070***
PHL	0.0000*	0.0002**	0.0002**	0.0003**	0.0008**	0.0065***
ROM	0.0001**	0.0005**	0.0005**	0.0008**	0.0016**	0.0021**
SGP	0.0000**	0.0002**	0.0002**	0.0004**	0.0010**	0.0049***
ZAF	0.0001**	0.0003**	0.0004**	0.0007***	0.0027***	0.0036***
SYR	0.0000**	0.0005***	0.0003**	0.0003**	0.0009**	0.0016**
THA	0.0000**	0.0002**	0.0003**	0.0004**	0.0008**	0.0041**
TTO	0.0000*	0.0003**	0.0002**	0.0003**	0.0026***	0.0121***
TUN	0.0001**	0.0007***	0.0002**	0.0003**	0.0006**	0.0010**
TUR	0.0001**	0.0006***	0.0005***	0.0006***	0.0015**	0.0025***
UGA	0.0000**	0.0003**	0.0002**	0.0002**	0.0027***	0.0013**
URY	0.0001**	0.0011***	0.0002**	0.0004**	0.0009**	0.0034**
VEN	0.0000**	0.0005***	0.0002**	0.0003**	0.0008**	0.0091***