Manfred M. Fischer

Spatial Externalities and Growth in a Mankiw-Romer-Weil World: Theory and Evidence

Paper

Spatial Externalities and Growth in a Mankiw-Romer-Weil World: Theory and Evidence*

Manfred M. Fischer[I]

Abstract

This paper presents a theoretical growth model that accounts for technological interdependence among regions in a Mankiw-Romer-Weil world. The reasoning behind the theoretical work is that technological ideas cannot be fully appropriated by investors and these ideas may diffuse and increase the productivity of other firms. We link the diffusion of ideas to spatial proximity and allow for ideas to flow to nearby regional economies. Through the magic of solving for the reduced form of the theoretical model and the magic of spatial autoregressive processes, the simple dependence on a small number of neighbouring regions leads to a reduced form theoretical model and an associated empirical model where changes in a single region can potentially impact all other regions. This implies that conventional regression interpretations of the parameter estimates would be wrong. The proper way to interpret the model has to rely on matrices of partial derivatives of the dependent variable with respect to changes in the Mankiw-Romer-Weil variables, using scalar summary measures for reporting the estimates of the marginal impacts from the model. The summary impact measure estimates indicate that technological interdependence among European regions works through physical rather than human capital externalities.

JEL Classification: C31, O18, O47, R11, R15

Keywords

Spatial economics, spatial econometrics, growth empirics, human capital externalities, physical capital externalities, technological interdependence, European regions

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[I] Institute for Economic Geography and GIScience, Vienna University of Economics and Business, Vienna, Austria

Corresponding Author:
Manfred M. Fischer, Institute for Economic Geography and GIScience, Vienna University of Economics and Business, Welthandelsplatz 1/Building D4, 1020 Vienna, Austria, e-mail: manfred.fischer@wu.ac.at

Introduction

Theoretical and empirical analysis of regional growth has a long history with neoclassical approaches dating back to Borts and Stein (1964). But the subject has been rather marginal to the mainstream of economics. This has begun to change in the past two decades, with the renaissance of interest in growth theory in the late 1980s accompanied by a related interest in regional growth processes (Roberts and Setterfield 2010). This latter interest has been stimulated by deepening European integration and spurred by the development of Eurostat's Regio database.

Neoclassical growth theory, largely built on the work of Solow (1956) and Mankiw, Romer and Weil (1992), has essentially shaped the way in which regional economic growth is approached in applied growth analysis (see Abreu 2014 for a survey). This theory views growth as having two driving forces: accumulation of (physical and human) capital and technological progress. In the original formulation of the theory, technology is conceived as codified (explicit) knowledge, a set of blueprints for turning inputs into outputs, and viewed as a pure public good costlessly available to all. In a common phrase, technology is like "manna from heaven" in that it descends upon the regions automatically and regardless of whatever else is going on in the regions. This means that all regions effectively use the same technology, and output per worker differences between them are explained by differences in capital per worker. Hence, regions may differ in their population growth rates but – given that these growth rates are exogenous parameters – all regions accumulate capital per worker until they reach their steady-state equilibrium level of capital per worker. At the steady-state, capital per worker is constant over time because new investment in capital is exactly offset by depreciation of existing capital and dilution of capital per worker due to population growth. Once regions reach their steady-state, further growth is only possible due to technological

change that is treated as exogenous to the economy and thus taken as a given parameter (Lutzker 2003).

This standard theoretical growth model has some peculiar features as a story of interregional differences in output levels. It implies that current output levels differ mainly because of past capital accumulation decisions and population growth rates. Thus, the model rules out any other differences between regions. It also implies that technology is a crucial source of long-run growth, but tells us nothing about technological externalities across regions.

Theoretical work on economic growth by Romer (1986) and Lucas (1988) has successfully demonstrated that aggregate externalities to physical and human capital within economies may help to explain many of the observed patterns of growth across economies. Romer (1986) and Lucas (1988) assume that each economy's aggregate level of technology increases with the aggregate level of physical and human capital, available in that economy. They argue that private capital accumulation generates new technological ideas which cannot be fully appropriated by the investors and thus increase the productivity of other firms in that economy. We take this argument one step further and allow for some of these technological ideas to spill over to neighbouring economies. Allowing technological ideas to cross borders to just a small number of neighbouring regions yields interesting conclusions in a Mankiw-Romer-Weil world of technologically interdependent economies.

The remainder of the paper is organized as follows. The next section sets out the theoretical growth model that accounts for technological interdependence among regional economies in a Maniw-Romer-Weil world. In the theoretical model we specify dependence of one region on only neighbouring regions at the outset. But through the magic of solving for the reduced form of the model and the magic of spatial autoregressive processes, the final theoretical and associated empirical model form is such that each region potentially depends

on all other regions, not just the few neighbours that made up our initial model specification. This implies that conventional regression interpretations of the parameter estimates would be wrong. But thanks to the work of LeSage and Pace (2009) we can actually quantify and summarize the complicated set of non-linear impacts that fall on all regions as a result of changes in the Mankiw-Romer-Weil variables in any region, using scalar summary impact measures. Furthermore, we can decompose these impacts into direct and indirect (externalities) effects.

In the final section we use data for a system of 198 regions across 22 European countries to test the predictions of the model and to draw inferences regarding the existence and magnitude of cross-regional physical and human capital externalities. The results provide evidence that technological interdependence in Europe works through cross-regional physical rather than human capital externalities.

The theoretical growth model with spatial externalities

Consider a system of *N* regions. These regions are similar in that they have the same production possibilities. They differ because of different endowments and allocations. Within a regional economy *i*, all agents are identical. The economies evolve independently in all respects, except that they are technologically interdependent. Total output of region *i* at time *t*, $Y_i(t)$, is given by an aggregate Cobb Douglas production function exhibiting constant returns to scale in labour and reproducible physical and human capital:

$$Y_i(t) = A_i(t)\ K_i(t)^{\alpha_K}\ H_i(t)^{\alpha_H}\ L_i(t)^{1-\alpha_K-\alpha_H} \tag{1}$$

where *K* is physical capital, *H* human capital, *L* labour input, and *A* is the aggregate level of technology. The α-coefficients, α_K and α_H, denote the output elasticities with respect to

physical and human capital, respectively. We assume that the sum of these output elasticities is smaller than one, which implies that there are decreasing returns to both types of capital.

Letting lower case letters denote variables normalized by the size of the labour force (so that $y_i(t) = Y_i(t) / L_i(t)$, for example), then the production function in intensive form may be written as

$$y_i(t) = A_i(t)\ k_i^{\alpha_K}(t)\ h_i^{\alpha_H}(t). \tag{2}$$

We now discuss each element of this poduction function in turn. First, physical capital per worker evolves according to

$$\dot{k}_i(t) = s_i^K y_i(t) - (n_i + \delta)\ k_i(t) \tag{3}$$

where the term on the left-hand side of the equation is the continuous time version of $k_i(t+1) - k_i(t)$, that is, the change in the per worker physical capital stock per time period. We use the dot notation to denote a derivative with respect to time: $\dot{k}_i(t) \equiv dk_i(t)/dt$. s^K is the physical capital investment rate, *n* the rate of labour force growth[1], and δ is a constant rate of depreciation.

Second, following Mankiw, Romer and Weil (1992) we assume that the same production process applies to human capital, physical capital and consumption so that one unit of consumption can be transformed costlessly into either one unit of physical capital or one unit of human capital. In addition, we make the simplifying assumption that human capital depreciates at the same rate as physical capital. Then Eq. (4) describes how per worker human capital is accumulated

$$\dot{h}_i(t) = s_i^H y_i(t) - (n_i + \delta)\ h_i(t)\,. \tag{4}$$

with s^H denoting the human capital investment rate.

Third, labour L_i at time *t* is assumed to grow exogenously at a constant rate, given by

$$L_i(t) = L_i(0)\ \exp(n_i\ t) \tag{5}$$

where $L_i(0)$ is initial supply of labour and n_i the labour force growth rate in region *i*.

The final factor in the production of output is the stock of technology, *A*. In the model, technology represents the only link between regions, there is no trade in goods, and capital and labour are not mobile. In the Mankiw-Romer-Weil model it is assumed that technology created anywhere in the world of regions is immediately available to be used in any region. Of course, this assumption about technology is unrealistic. Not every region faces the same *A* in the production function. Another way to stating this is that regions choose the best technologies available to them (that is, they are perfectly efficient). But their choice is limited by the fact that not all existing technologies are appropriate for a given region[2]. Depending on the region's relative stocks of physical and human capital, some technologies may be more or less productive than others.

We assume[3] that the aggregate level of technology in region i, A_i, may not only depend on externalities generated by physical and human capital accumulated in that region in or before time period t, described by $k_i(t)^{\phi_K} h_i(t)^{\phi_H}$ with $0 \le \phi_K, \phi_H < 1$, but also on the aggregate level of technology of its neighbouring economies, $A_j(t)$ with $j \neq i$. In line with Ertur and Koch (2007), and Fischer (2011), we assume the following functional form for the level of technology in region *i* at time *t*,

$$A_i(t) = \Omega(t)\ k_i(t)^{\phi_K}\ h_i(t)^{\phi_H} \prod_{j \neq i} A_j(t)^{\rho W_{ij}} \ . \qquad (6)$$

The first term on the right-hand side of the equation, $\Omega(t)$, represents some amount of technological knowledge, created anywhere in the system of regions, which is immediately available to be used in any region. This part of technological progress is – as in the traditional version of the neoclassical growth model – identical in all regions and grows at a constant rate μ in all regions: $\Omega(t) = \Omega(0)\exp(\mu t)$ with $\Omega(0)$ denoting initial technology. The next two terms suppose that each region's i aggregate level of technology, $A_i(t)$, increases with accumulated factors. It increases with per worker physical capital, $k_i(t)$, reflecting the learning-by-doing process emphasized by Arrow (1962) and Romer (1986), and it increases with per worker human capital, $h_i(t)$, reflecting human capital externalities as underlined by Lucas (1988). The technical parameters ϕ_K with $0 \leq \phi_K < 1$ and ϕ_H with $0 \leq \phi_H < 1$ reflect the spatial connectivity of k_{it} and h_{it} within region i, respectively[4].

Technological interdependence between regions may arise from physical and/or human capital externalities that cross the regional boundaries. The last term on the right-hand side of Eq. (6) serves to account for such externalities so that the level of technology in region i may also depend on the level of technology, $A_j(t)$, in other regions j $(j \neq i)$. The scalar parameter ρ with $0 \leq \rho < 1$ describes the degree of technological interdependence among regions. Each region has a differentiated access to foreign technology because of the connectivity terms, denoted by W_{ij}. These connectivity terms[5] are elements of a conventional N-by-N spatial weight matrix W which specifies a "neighbourhood" set for each region i. In each row i, a non-zero element W_{ij} defines j as being a neighbour of i. By convention, a region is not a neighbour to itself, so that the diagonal elements W_{ii} are zero for i=1, …, N. We will also

assume that W is row-standardized from a symmetric matrix, so that all eigenvalues are real and less than or equal to one.

Thus, the level of technology in region i may depend not only on its own levels of physical and human capital per worker, but also on the levels of physical and human capital per worker in its neighbouring regions j. Resolving Eq. (6) for $A_i(t)$, and inserting the result in the production function, given by Eq. (2), we finally get the following theoretical growth model that accounts for externalities across regions in a Mankiw-Romer-Weil world[6]

$$y_i(t) = \Omega(t)^{\frac{1}{1-\rho}} \; k_i(t)^{u_{ii}} \; h_i(t)^{v_{ii}} \prod_{j \neq i} k_j(t)^{u_{ij}} \; h_j(t)^{v_{ij}} \tag{7}$$

with

$$u_{ij} \equiv \begin{cases} \alpha_K + \phi_K \left[1 + \sum_{r=0}^{\infty} \rho^r (W^r)_{ij} \right] & \text{for } i = j \\ \phi_K \sum_{r=0}^{\infty} \rho^r (W^r)_{ij} & \text{for } i \neq j \end{cases} \tag{8}$$

$$v_{ij} \equiv \begin{cases} \alpha_H + \phi_H \left[1 + \sum_{r=0}^{\infty} \rho^r (W^r)_{ij} \right] & \text{for } i = j \\ \phi_H \sum_{r=0}^{\infty} \rho^r (W^r)_{ij} & \text{for } i \neq j \end{cases} \tag{9}$$

where $(W^r)_{ij}$ is the (i, j)th element of the N-by-N matrix W^r, and W^r is the rth power of W. Note that the rows of the spatial weight matrix W are constructed to represent first-order contiguous neighbours. The matrix W^2, for example, reflects the second-order neighbours, etc. Since the neighbour of the neighbour (second-order neighbour) to a region i includes

region *i* itself, W^2 has positive elements on the main diagonal when each region has at least one neighbour.

The model described by Eqs. (6)-(8) reduces to the Solow growth model augmented with human capital as described by Mankiw, Romer and Weil (1992) when there are no externalities to capital accumulation within regions ρ, $\alpha_H = \phi_H = 0$, and technological ideas do not cross regional borders, $\rho = 0$.

From theory to empirics

Now consider solving for a balanced growth path, defined as a situation in which (i) physical and human capital grow at constant rates, and (ii) the physical and human capital investment rates and the population growth rate are constant. It is easy to show that along such a balanced growth path, the growth rates of the physical and human capital grow at the same rate denoted by

$$g \equiv \frac{\mu}{(1-\rho)(1-\alpha_K-\alpha_H)-\phi_K-\phi_H}. \tag{10}$$

Since the per worker production function given by Eq. (2) is characterized by decreasing returns, Eqs. (3)-(4) imply that the physical capital-output and human capital-output ratios for region *i* are constant so that

$$\frac{k_i^*(t)}{y_i^*(t)} = \frac{s_i^K}{n_i+g+\delta} \tag{11}$$

$$\frac{h_i^*(t)}{y_i^*(t)} = \frac{s_i^H}{n_i+g+\delta}. \tag{12}$$

The asterisk is used to signify the steady-state levels for *y*, *k* and *h*. Substituting these expressions into the per worker production function (7) and taking the logarithm leads to the following approximation of the behaviour of a region's per worker outcome in a neighbourhood of the steady state

$$\begin{aligned}\ln y_i(t) = {} & \tfrac{1}{1-\eta}\ln \Omega(0) + \tfrac{\alpha_K+\phi_K}{1-\eta}\ln s_i^K + \tfrac{\alpha_H+\phi_H}{1-\eta}\ln s_i^H - \tfrac{\eta}{1-\eta}\ln(n_i+g+\delta) \\ & - \tfrac{\alpha_K}{1-\eta}\rho\sum_{j\neq i}W_{ij}\ln s_j^K - \tfrac{\alpha_H}{1-\eta}\rho\sum_{j\neq i}W_{ij}\ln s_j^H + \tfrac{\alpha_K+\alpha_H}{1-\eta}\rho\sum_{j\neq i}W_{ij}\ln(n_j+g+\delta) \\ & + \tfrac{1-\alpha_K-\alpha_H}{1-\eta}\rho\sum_{j\neq i}W_{ij}\ln y_j(t)\end{aligned} \tag{13}$$

where η is defined as the sum of the output elasticities and the technical ϕ-parameters that reflect the spatial connectivity of the worker physical and human capital stocks in region *i*, respectively:

$$\eta \equiv \alpha_K + \alpha_H + \phi_K + \phi_H \,. \tag{14}$$

At a first glance, one would be tempted to state that per worker output (of region i at steady-state) positively depends on its own physical and human capital investment rates s^K and s^H, and negatively on its labour growth rate n. But this would be only true in the special case when there are no externalities within the region, $\phi_K = \phi_H = 0$, and technological ideas do not cross regional boundaries, implying that Eq. (13) collapses to the classical Mankiw-Romer-Weil model with independent regions. In its general form, Eq. (13) is a model specification that includes spatial lags of both the dependent and independent variables, known as Spatial Durbin Model (SDM) in the spatial econometrics literature.

We see that a logical consequence of the simple dependence of region i on a small number of nearby regions $j \neq i$ in Eq. (6) leads to a final-form model outcome where changes in a single region can impact all other regions. Of course, we must temper this result by noting that there is a decay of influence as we move to more distant or less connected regions. It also means that conventional regression interpretations of the parameter estimates would be wrong, as noted by LeSage and Fischer (2008), and LeSage and Pace (2009).

The implied econometric specification of the theoretical model

In accordance with Mankiw, Romer and Weil (1992) we argue that the term $\Omega(0)$ should be interpreted as reflecting not just technology, which Mankiw, Romer and Weil (1992) assume to be constant across space, but as reflecting region-specific influences on growth such as resource endowments, climate and institutions. Hence, we may assume that these differences vary randomly in the sense that $\Omega(0) = \beta_0 + \varepsilon_i$ where β_0 is a constant and ε_i is a region-specific shock distributed independently of s_i^K, s_i^H and n_i, and this can be used to justify an error term. Hence, the empirical counterpart of the reduced form of the theoretical growth model in Eq. (13) can be expressed at a given time (t=0 for simplicity) in matrix form as follows

$$y = \beta_0 \iota_N + X\beta + WX\gamma + \lambda Wy + \varepsilon \tag{15}$$

where y is an N-by-1 vector of the dependent variable representing the (logged) output per worker levels for the N regions. X is the N-by-3 matrix of observations on the three Mankiw-Romer-Weil determinants in log form, and β the associated 3-by-1 parameter vector. ι_N is the N-by-1 vector of ones with the associated scalar intercept coefficient β_0.

W is an *N*-by-*N* spatial weight matrix that describes the spatial connections between the regions. The matrix contains fixed values, which sum to one across each row, so that all eigenvalues are real and less than or equal to one. The matrix product *N*-by-3 *WX* reflects an average of (logged) physical and human capital and population levels in neighbouring regions, and γ is the associated 3-by-1 vector of regression coefficients. Similarly, the *N*-by-1 vector *Wy* reflects an average of (logged) levels of per worker output in neighbouring regions. λ is a scalar parameter[7] that measures the strength of spatial dependence with boundaries on the permissible (stationary) parameter space determined by the min. and max. eigenvalues of the *N*-by-*N* matrix *W*. ε is an *N*-by-1 vector of random disturbances. We assume ε to be normally distributed with zero mean and constant variance. The parameters of the model can be estimated using maximum likelihood, Bayesian, or instrumental variable methods.

An examination of the data generating process for this model shown in Eq. (16) makes it clear that the empirical counterpart model of our theoretical model reflects a non-linear relationship between *y* and the right-hand side terms ι_N, X and ε

$$y = (I_N - \lambda W)^{-1}(\beta_0 \iota_N + X\beta + WX\gamma + \varepsilon). \tag{16}$$

The inverse $(I_N - \lambda W)^{-1}$ can be expressed as an infinite sequence: $I_N + \lambda W + \lambda^2 W^2 + \lambda^3 W^3 + \ldots$, and the matrix product WX represents a linear combination of the Mankiw-Romer-Weil variables from neighbouring regions. The matrix product W^2X is a linear combination involving neighbours to the neighbouring regions (sometimes called second-order neighbours). Diagonal elements of W^2 are not zero, since regions are by definition neighbours to neighbours. A similar statement regarding non-zero diagonal elements could be made for higher-order matrix products, such as W^3X, which represents a

linear combination of neighbours to the neighbours, to the neighbours, and so forth for higher powers (LeSage and Pace 2014). This is consistent with the definition of global spillovers (LeSage and Pace 2009).

One implication of the non-linear relationship in Eq (16) between *y* and *X* is that the coefficients β_0, β and γ cannot be interpreted as if they reflect linear regression slope estimates. The econometrics literature interprets coefficients from such models using marginal effects that reflect partial derivatives indicating how changes in each explanatory variable impact the expected *y* outcomes. Hence, a proper way to interpret the results of model (15) has to rely on the three *N*-by-*N* matrices of partial derivatives of *y* with respect to changes in the *q*th explanatory variable

$$\frac{\partial y}{\partial X^q} = (I_N - \lambda W)^{-1}(I_N \beta_q + W\gamma_q). \tag{17}$$

Note that a system of 100 regions, for example, would produce a 100-by-100 matrix of responses for each of the three Mankiw-Romer-Weil determinants, even though many of these responses would be equal to zero if *W* is sparse, and this poses a real problem for reporting estimates of the marginal impacts from this model.

As a solution to this issue LeSage and Pace (2009) suggested taking the mean of the main diagonal elements of the *N*-by-*N* matrices in Eq. (17) to construct a scalar summary of the direct effects. These measures show how changes in the *q*th Mankiw-Romer-Weil determinant for the *i*th region impact the *i*th region's output, for *i*=1,…,*N*. In addition, these authors proposed using the mean of the (cumulated) off-diagonal elements as a summary of the cumulative indirect or spillover effects. These scalar summary measures can be interpreted as representing how a change in the *q*th explanatory variable in the typical or representative

region *j* impacts outcomes *y* for the typical region *i*. Specifically, the elements in the *i*th row of the *N*-by-*N* matrix of partial derivatives of *y* with respect to changes in the *q*th explanatory variable, $\partial y_i / \partial X_j^q$ for $j \neq i$, $(j = 1,...,N)$, reflect how changes in each of the regions' *q*th Mankiw-Romer-Weil determinant impact outcomes in the *i*th region.

In addition to calculating point estimates for the scalar summary measures, we need measures of dispersion for inference. Given an estimate of the standard deviation for the scalar summary point estimates, we can test hypotheses regarding the significance of the direct and indirect effects for each of the Mankiw-Romer-Weil variables. For maximum likelihood estimates, measures of dispersion can be constructed by simulating values for the parameters from the estimated variance-covariance matrix. These simulated values (say, 10,000 values) for the model parameters λ, β and γ can be used in Eq. (17) to produce 10,000 values for the scalar summary effects estimates. Taking the median of these simulated summary measures provides a point estimate for the summary measures, and allows inference on the direct and indirect (spillover) impacts. It is worth noting that LeSage and Pace (2009) provide a computationally efficient approach to processing the draws to generate empirical distributions for the direct and indirect impact estimates. This approach has been implemented in the Spatial Econometric Toolbox for MATLAB (LeSage 1999).

Regions, data and estimation results

Before the question can be considered whether data for European regions support the predictions by our theoretical growth model, an obvious and fundamental question that must be addressed is that of how to define a region. Studies of European regional growth have typically utilized NUTS definitions of regions. NUTS is an acronym of the French for the "nomenclature of the territorial units for statistics", denoting a hierarchical system of regions used by the statistical office of the European Community for the production of regional

statistics. At the top of the hierarchy are the NUTS-0 regions (countries), below which are NUTS-1 regions (regions within countries), and then NUTS-2 regions (subdivisions of NUTS-1 regions).

NUTS regions are defined according to normative rather than functional criteria (corresponding to institutional/administrative boundaries) and hence represent a less satisfactory definition of the region for the purpose of analysing regional growth. Since data on functionally defined economic regions (Cheshire and Carbonaro 1995) is not publicly available we use NUTS-2 regions as units of observation. These regions, though varying in size, are generally considered to be the most appropriate spatial units for modelling and analysis purposes (Fingleton 2001). In most cases, they are sufficiently small to capture subnational variations. However, we are aware that their delineation does not represent the boundaries of regional growth processes very well. The choice of the NUTS-2 level might also give rise to a form of the modifiable areal unit problem, well known in geography (see Manley 2014).

The sample regions include NUTS-2 regions (see Fig. 1) located in Western Europe and Eastern Europe. Western Europe is represented by 159 regions covering Austria (nine regions), Belgium (11 regions), Denmark (one region), Finland (four regions), France (21 regions), Germany (40 regions), Italy (18 regions), Luxembourg (one region), the Netherlands (12 regions), Norway (seven regions), Portugal (five regions), Spain (15 regions), Sweden (eight regions) and Switzerland (seven regions). Eastern Europe is covered by 39 regions including the Baltic states (three regions), the Czech Republic (eight regions), Hungary (seven regions), Poland (16 regions), Slovakia (four regions) and Slovenia (one region). The main data source is Eurostat's Regio database. The data for Norway and Switzerland were provided by Statistics Norway and the Swiss Office Fédéral de la Statistique, respectively.

Figure 1 about here

The data relate to the period from 1995 to 2004 when economic recovery in Eastern Europe gathered pace. The time period is relatively short due to a lack of reliable figures for the regions in Eastern Europe[8] (Fischer and Stirböck 2006). Output is measured in terms of gross value added in the year 2004, defined as the net result of output at basic prices less intermediate consumption valued at purchasers' prices. We measure *n* as the average growth rate of the working population (1995-2003), use the average gross fixed capital formation per worker as proxy for physical capital investment, and the level of educational attainment of the population (15 years and older) with higher education based on data for the active population aged 15 years and older that attained the level of tertiary education, as defined by the International Standard Classification of Education (ISCED) 1997 classes 5 and 6 (see UNESCO 2006), as a proxy for human capital investment. We suppose that the sum of the balanced growth rate g and the depreciation rate δ is equal to 0.05, a fairly standard assumption in the literature (see, for example, Bond, Hoeffler and Temple 2001, Fingleton and Fischer 2010). And we employ a binary first-order contiguity matrix, implemented in row-standardized form, to represent the neighbourhood structure among the regions.

In Table 1 we report the maximum likelihood estimates for the model, although these are not directly interpretable in terms of the impacts associated with changes in the growth determinants on the dependent variable. Table 1 also summarizes the implied values for the output elasticities (α_K and α_H), the two technical ϕ-parameters (ϕ_K and ϕ_H), and ρ that measures the degree of technological interdependence between the regions[9]. For completeness, it is worth noting that a common factor test using likelihood ratios rejects the three non-linear restrictions $\gamma_1 + \beta_1\lambda = 0$, $\gamma_2 + \beta_2\lambda = 0$, and $\gamma_3 + \beta_3\lambda = 0$. The likelihood is 225.61 for the SDM specification and 192.69 for Mankiw-Romer-Weil model with spatial error terms, both based on the binary first-order contiguity matrix and non-constrained

maximum likelihood estimation. This leads to a difference of 32.92, indicating a rejection of the spatial error model in favour of the spatial Durbin model specification using the 99% critical value for which $\chi^2(3)$ equals 11.34. Thus, the test provides no evidence that the empirical counterpart of our theoretical growth model would collapse to a spatial error model version of the classical Mankiw-Romer-Weil model[10].

Table 1 about here

The proper way to interpret the spatial Durbin model results is in terms of the effects estimates outlined in Table 2. A set of 10,000 random draws from estimation was used to construct standard deviations and *p*-values for these impact estimates. The scalar summary effects estimates average over all the regions in the sample. Direct (own-region) effects responses in Table 2 indicate positive and significant (intraregional) spatial externalities from physical and human capital stocks. The impact estimates differ from the coefficient estimates for physical and human capital outlined in Table 1. The difference is due to some feedback effect that comes into play in the direct effects estimates. There are negative, but not significant direct impacts associated with changes in population growth.

Table 2 about here

Since the empirical model is specified by using a log-transformation of both dependent and independent variables, the direct effects estimates can be interpreted as indicating that a ten percent increase in physical capital in region *i* would ceteris paribus result in a 5.8 percent increase in regional output per worker in this region. And a ten percent increase in human capital in region *i* would result in a 1.5 percent increase in regional output per worker.

Table 2 also shows the cumulative indirect (cross-regional spatial spillover or externalities) effects associated with a change in physical and human capital. Here we see positive and significant externalities from physical capital stocks. The magnitude is such that a ten percent in physical capital stocks of neighbouring regions would lead to a 2.7 percent (long-run) increase in regional output of region *i*. The cumulative spillover magnitude of 0.27 appears to be rather large when compared to the direct effects magnitude of 0.58. But these are cumulative spatial externalities, where the cumulation takes place over all neighbouring regions, neighbours to the neighbouring regions and so on. Effects falling on any individual region[11] are much smaller, consistent with spillovers being a "second order effect".

Note that it would be a mistake to interpret the γ-estimates as representing spatial externalities magnitudes. If we would incorrectly view, for example, the SDM coefficient estimate on the spatial lag of the human capital variable (γ_2) as reflecting the indirect impact, this would lead to an inference that human capital stocks in neighbouring regions would exert a negative and significant indirect (spatial spillover) impact on regional output. But the true impact estimate points to cross-regional human capital externalities that are not significantly different from zero (p=0.28). The elasticity responses revealing the increases in population levels for neighbouring regions have a positive and significant impact on region output (per worker) levels. The magnitude is about four times that of physical capital. The magnitude of (cumulative spillovers) impact is 1.07, but the impact falling on a single neighbouring region would be much smaller for the reasons indicated in the discussion of physical capital stock cumulative spatial externalities.

Closing remarks

This paper suggests a theoretical growth model with spatial externalities across regional economies that extends the Mankiw-Romer-Weil model to account for technological

inderdependence among regions. In this model we specified dependence of one region on only a small number of neighbouring regions at the outset. However, through the magic of solving for the reduced form of the model and the magic of spatial autoregressive processes, the final form is such – and this is an important theoretical result of this study – that each region potentially depends on all other regions, and not just the few neighbours that make up our initial model specification/construction.

The model, tested using a system of 198 regions across 22 European countries has several implications that are worth noting. *First*, interregional technological interdependence implies that regions cannot be analysed in separation, but must be analysed as an interdependent system, and theoretical growth models have to account for technological interactions among regions. *Second*, the predictions of the theoretical growth model outlined in this paper yield a better understanding of the role played by geographic location and spatial externalities in regional growth processes, and show that the textbook Mankiw-Romer-Weil model is misspecified since variables representing spatial interaction effects are omitted. *Third*, a correct interpretation of the model has to use marginal effects that reflect partial derivatives indicating how changes in an explanatory variable impact the expected outcome of the dependent variable, an important point frequently overlooked in the spatial econometrics literature. *Finally*, the model results indicate that changes in physical capital produce spatial spillovers to neighbouring regions, whereas changes in human capital do not. This implies that technological interdependence in Europe works through cross-regional physical (rather than human) capital externalities.

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[1] An important assumption that will be maintained throughout the paper is that the labour force participation rate is constant over space and time, and the population growth rate is given by the parameter *n*. This implies that the labour force growth rate, $\dot{L} / L$, is also given by *n*.

[2] For example, one can think of technologies requiring the intensive use of skilled labour, or an appropriate match of skilled labour and machines (e.g., computers). Hence, the most productive technologies may be inappropriate for developing regions and, even if adopted, do not raise the total factor productivity levels.

[3] We assume hereby that each unit of capital investment increases not only the stock of capital, but also generates externalities, which lead to knowledge spillovers that increase the level of technology for all firms in the region.

[5] It is important to note that the connectivity terms W_{ij} should be exogenous to the model to avoid identification problems as emphasized by Manski (1993) in the context of social science models.

[6] For the derivation see Fischer (2011).

[7] Note that $\lambda = (1-\alpha_K-\alpha_H)\rho(\eta-1)^{-1}$ with $\eta = \alpha_K + \alpha_H + \phi_K + \phi_H$.

[8] The political changes since 1989 have resulted in the emergence of new or re-established states (the Baltic states, the Czech Republic, Slovakia and Slovenia) with only a very short history as sovereign national entities. In most of these states, historical data series simply do not exist. Even for states such as Hungary and Poland that existed for much longer time periods in their present boundaries, the quality of data referring to the period of central planning imposes serious limitations on analysing regional growth. This is closely related to the change in accounting conventions, from the material product balance system to the European System of Accounts 1995. Cross-regional comparisons require internationally comparable regional data, which are not only statistically consistent but also expressed in the same numéraire. The absence of market exchange rates in the former centrally planned economies is a further impediment.

[9] The implied parameter values, their standard deviations and *p*-values were computed based on the simulation technique with 10,000 random draws.

[10] This result is in line with Fingleton and López-Bazo (2006) questioning the credibility of specifications with dependence structures in the error terms.

[11] This can be seen by considering that on average there are four to five first order neighbours, so if we divide the spillover/indirect effects by a factor four (five), the marginal impacts of 0.066 (0.053) associated with a single region are much smaller than the direct effects. Further note that in reality we should divide by a number much greater than the first order neighbours, since these effects emenate out to more distant neighbours.