OPTIMAL GROWTH, COORDINATION AND SUSTAINABILITY IN THE SPATIAL ECONOMY

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Abstract

Until recently, the interaction between environmental quality, economic activity and growth is predominantly considered in an a-spatial context. Traditional neoclassical growth theory following Solow/Swan has mainly addressed questions about environmental and resource limits to growth. Recently, much attention is also devoted to the environment-growth interface from an endogenous growth perspective. However, an important element that is missing in both the neoclassical and endogenous growth approaches is a multiregional perspective. The present theoretical study tries to present one of the first attempts to fill this gap. The analysis is based on a model of two interactive regions, with possible interaction between the regional environments via the global environment. The implications of this type of analysis are manifold. One is that endogeneity of growth is not only due to technology and knowledge formation but also to the effects of trade, resource scarcity and environmental degradation. Another implication is that a coordinated environmental policy of regions should address long-term sustainability, and take account of the positive technological and negative environmental dynamic externalities.

1. Introduction

The issue of environmental quality and long-run economic growth in a spatial or multi-regional context has been largely ignored by economists. A first attempt to analyze this problem is offered here, based on the use of dynamic descriptive and optimization frameworks. First, an overview is given of economic approaches providing relevant inputs for a more comprehensive study of the relation between multiregional growth, trade, environment and policy coordination. Subsequently, a prototype dynamic two-country model is presented which can address some of the main questions in this context.

The relationship between environmental quality and spatial economic processes is extremely important, but has until now not received very much focused attention from either regional or environmental economics. A general introduction is provided by Siebert (1985 and 1996). The lessons for environmental policy makers from the existing - mainly theoretical - literature on spatial environmental externalities include mainly adjustments or extensions of Pigouvian charges and taxation. These corrections are motivated by endogenous location, imperfect markets, international trade power, international coordination of policy (for national, transboundary and global problems) and long-term sustainability (see, e.g., Anderson and Blackhurst, 1992; Markusen *et al.*, 1993; Motta and Thisse, 1994; Carraro, 1994). These corrections go in different directions. In the case of imperfect markets, trade power and endogenous locations, the standard Pigouvian tax should be corrected downwards. In the case of transport related externalities, endogenous technology and sustainability a tighter policy is needed. An integrated treatment of these issues has not received a great deal of attention so far.

Few models have been able to simultaneously address these various aspects. In the context of a static spatial equilibrium model the link between environmental regulation, trade, transport and spatial economic structure is addressed by Verhoef and van den Bergh (1996) and Verhoef *et al.* (1997). They derive policy rules under first- and second-best conditions, the latter case relating to a transport tax regime which compensates for disoptimal production taxes in regions that have not implemented an optimal environmental policy. Van den Bergh and Nijkamp (1995) perform numerical simulations with a dynamic descriptive model of growth, trade and environment. They consider different scenarios, including symmetric and asymmetric regions, and the latter case also with technology diffusion. It is shown that growth and technology formation may either stimulate or harm long-run sustainability, as they enhance the capacity for resource-efficient and resource-intensive growth. The present paper aims to improve upon this analysis, based on a more consistent formulation of trade as well as investments, i.e. the engine of growth, in each region, as well as the consideration of coordination versus non-coordination growth problems.

In Section 2 the interdependence between environmental sustainability on a regional scale and regional economic growth, and the interpretation of endogenous growth in an environment-space context are discussed in more depth. A general framework for multiregional growth and environment is considered in Section 3. A prototype model is presented in Section 4. It integrates multiregional growth, environmental processes and multiregional trade. Furthermore, it considers the cases of coordinated and independent regional environment-growth policy in an optimization framework. Some numerical dynamic simulation results obtained with a specific variation of this model are discussed in Section 5. Section 6 offers concluding remarks.

2. Growth, environment and trade

The potential conflict between environmental quality and economic growth is a topic which has attracted a lot of interest and generated much debate among economic growth theorists. For instance, neoclassical economic growth theory has frequently been applied to issues of renewable resource limits, long run pollution effects and sometimes even to a combination of these (for an early survey, see Kamien and Schwarz, 1982; for recent contributions, see Tahvonen and Kuuluvainen, 1991 and 1993). Analyses in this flavour have focused on the role of substitution between man-made capital and natural resources materials in production, technological improvements in materials efficiency of production, and backstop technologies (see Dasgupta and Heal, 1979). The issue of sustainability has also been explicitly treated, although there is no agreement as to its theoretical interpretations (see, e.g., Toman *et al.*, 1994). Conservation-preservationist's and exploitationist's views are linked to the distinction between strong and weak sustainability (Pearce and Turner, 1990), with the Hartwick rule of investing resource rents in man-made capital as an extreme case of the latter (Hartwick, 1977; Gutés, 1996). A survey of alternative approaches to modelling for sustainable development is given in van den Bergh and Hofkes (1997), including attention for endogenous growth, evolutionary change, integrated models, general equilibrium models, macroeconomic models, etcetera.

The issue of sustainability in a multiregional context has attracted little attention. One approach is to consider regions as open systems, both in terms of economic and environmental processes (e.g., van den Bergh and Nijkamp, 1991). Another approach is to described multiregional systems completely and explicitly. Regional economics provides a limited perspective for theory regarding multi-regional dynamics (see Anderson and Kuenne, 1986; and Walz, 1997). Spatial price equilibrium theory offers one approach (see Verhoef and van den Bergh, 1995), while spatial general equilibrium models offer a more complete but complex alternative (Roson, 1994; van den Bergh *et al.*, 1996). Finally, game-theoretic models may be used to deal with specific questions of environmental policy coordination (e.g., Van der Ploeg and De Zeeuw, 1992; Batabyal, 1996).

The extension of the Solow-Swan growth framework with various types of endogenous learning and technology mechanisms by Stokey, Romer and Lucas and others has generated a wealth of literature on endogenous growth since the end of the 1980s. Various recent articles and books provide good overviews (Romer 1994; Mankiw, 1995, Pasinetti and Solow, 1994; and Barro and Sala-i-Martin, 1995). Different contributions to the new growth theories focus on the role of various externalities related to technological change, specialisation and trade, monopoly rents from innovation and "creative destruction", human capital and government policy. Although economic growth theory with environment and resources is dominated by the Solow-Wan tradition (see Toman et al., 1995), there have been several attempts already to model and endogenise technical progress within models designed to address environmental issues and sustainability (e.g., Gradus and Smulders, 1993; van den Bergh and Nijkamp, 1994; Bovenberg and Smulders, 1995). These models do not simultaneously address spatial disaggregation, interregional trade and interaction between local and global environmental quality. The focus in the economic models nowadays is usually on endogenous technology and knowledge formation, mixing such positive externalities with negative environmental externalities, and arriving at more optimistic conclusions than in neoclassical growth models with exogenous technology. The influence of pollution and preferences on technology choice is important in this respect. These results are often stated against conclusions obtained with global "limits to growth" models (Meadows *et al.*, 1972 and 1992). These lack advanced technology, price mechanisms, producers' and consumers' behaviour, and interregional trade submodels, and have therefore been heavily attacked by economists (e.g., Nordhaus, 1973 and 1992). Alternative approaches to the relationship between technology, growth and environment have stressed its disequilibrium, uncertainty and evolutionary/Schumpeterian character (e.g., Dosi *et al.*, 1988; and in an environmental context; Faber and Proops, 1990; Erdman, 1993; Clark *et al.*, 1995). Whereas economists have been much concerned with the potential conflict between economic dynamic efficiency and environmental sustainability, several other approaches focus on controllability (Perrings, 1991) and stability, the latter often based on ecological theory or metaphors (Holling, 1986 and 1994). Common and Perrings (1992) provide an interesting and systematic comparison of the alternative views.

Endogenous growth in a spatial-environmental context allows for more interpretations and elaborations as compared with that in a non-environment and a-spatial setting. A fundamental point to note as a start is that there do in fact not exists "real" exogenous factors of production. One can easily see that all production factors are the output of some economic process. So labour is produced with exergy (useful energy), materials, capital and labour; exergy is "produced" with exergy, materials, capital and labour; capital is produced with exergy, materials, capital and labour. Materials are "produced" with exergy, materials, capital and labour. Knowledge is here assumed to be incorporated in capital and labour. Resource scarcity and environmental regulation may act as incentives to promote specific technological progress and growth (see Faber and Proops, 1990).

In a spatial context trade can be considered as a motor of growth (Grossman and Helpman, 1991). Also transport can be included in the production function on an aggregate level, representing a unique, essential and explicit reference to the spatial dimension (e.g., Walz, 1997). Endogenous growth theory in a spatial-environmental context could then pay attention to the various important (policy) questions. First, there are questions related to the rate of growth: can diminishing returns to regional investment be overcome due to multiregional trade, and is regional growth slowed down due to multiregional environmental factors and regulation? Second, there are questions relating to the direction of growth: do enviromental feedbacks to the economy cause a shift to more trade, to more domestic production, to more dirty or clean production, and - associated with this - to dirty or clean export and import?

Some of these question can be addressed by the models presented in the following sections.

3. A general framework for analysis of multiregional growth and environment

A logical starting point in the context of growth and environment is the existence of a finite natural carrying capacity (CC), measured in physical resource use and/or emissions (or other types of environmental disturbance, like land use) which would act as a limiting factor to the scale of the economy. Some possible patterns of economic scale and CC over time are shown in Figures 1 and 2. The standard density dependent (versus exponential) growth pattern, restrained by some limiting factor (resource), defining the respective carrying capacity, is represented in Figure 1. It shows a monotonic convergent pattern, and a cyclic pattern. The latter can occur when processes are non-deterministic, or in open systems like regions. When one, as in our case, is interested in two-way interactions between economic and ecological systems, variations in the carrying capacity should clearly be allowed for. These have only a meaning if they go along with an endogenization of the CC, namely by making it dependent on the scale of the economy. This is illustrated in Figure 2. A feedback process between the CC and the economic scale can then give rise to a variety of patterns of the economic scale indicator: monotonic and stable or unstable; or cyclical (not all these are shown in Figure 2).

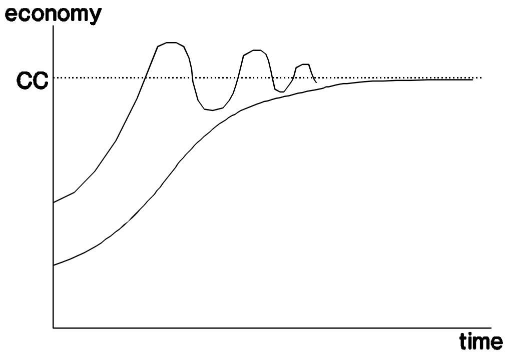

Figure 2. Fixed carrying capacity with two possible patterns of economic growth.

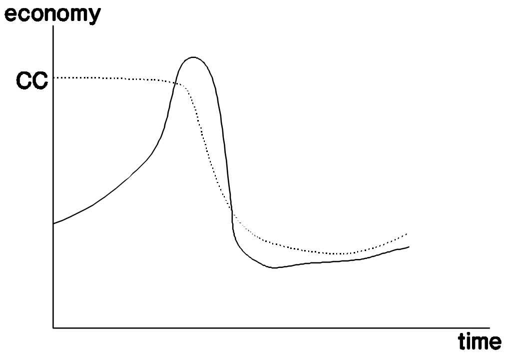

Figure 2. Variable carrying capacity with two-way interaction between economy and environment.

This simple picture provides a general conceptual framework for studying the interaction between growth and environment on global and regional scales. In the latter context, it has, in addition, to be realized that one may envision two types of CC, namely one relating to a closed, and one to an open region. Trade beyond the regional boundaries causes the open region's carrying capacity to differ from the closed region's one (in fact, to be larger). This would then allow the open region's economy to attain a larger scale than the closed one's. However, when opening up a region, the closed region's CC level may be exceeded due to trade. This may cause destruction of the components of the closed region's CC. This in turn will also negatively affect the open region's CC, which is partly based on the factors supporting the closed region's CC, i.e. the region-internal factors or resources. Subsequently, this may negatively impact upon the the regional economy. The model in Figure 2 can in fact also be regarded as relevant to illustrate the latter unfortunate process.

In van den Bergh (1993) a simple model is considered that can represent the process in Figure 2. One set of assumptions represents a case where both internal (behavioural) and external environmental feedbacks to economic growth are operational. It turns out to lead to one interior stable equilibrium. Furthermore, three general types of pattern characterise all possible behaviour far from equilibrium. These are dependent on the inclusion and intensity of the feedback mechanisms between the economy and the environment. The present study aims to provide for a more detailed model consistent with the basic framework just sketched, and formalizing the relation between endogenous growth, endogenous environmental change and endogenous regional trade.

Incorporating these three main elements in a single model is a very difficult task and clearly calls for heroic assumptions as well as alternative models and specifications. A two-regional setting is chosen here, which allows us to deal with imports and exports in one region causing unsustainable patterns in the respective region or in the other region, via interregional trade. This may be referred to as "importing sustainability and exporting unsustainability". The model allows for tracing the mutual impact of changes in the global and local or regional environment, and the repercussions of these in terms of consumption, production and interregional trade. It may therefore be regarded as a prototype model of larger and more complex integrated climate-change/social-impact models. The model incorporates the following elements:

- production and consumption processes in the regional economies, and interregional trade;
- regional environmental processes interact through the global environment, and are a link between generation and reception of environmental externalities;
- endogenous technology allows for more efficient use of material resources in production;
- there is diffusion of technology from one region to the other (having the benefit of avoiding full symmetry as well as limiting model complexity);
- regional welfare is a function of indicators for consumption, and for regional and global environmental quality.

4. Optimal multiregional growth with environment

Considering optimal growth in a multiregional setting from a standard perspective, i.e. based on maximizing a discounted stream of utility over time, leads to a two sub-problems. In the first one each region strives for optimal growth given the decisions made in the other region, in other words, a dynamic Nash equilibrium results. A social optimum however would require coordination, as there are two types of externalities: negative externalities if the regional environments are connected (we have not spoken about cross-boundary flows, but these might be implicit in the global-regional environment connections); furthermore, there are positive externalities due to diffusion of technological innovations from region A to region B.

In each region (j=A,B) relevant control variables, i.e. investment in capital (in both regions) and technological innovation (only in region A), I^{j}_{K} and I^{A}_{T} , and two different consumption goods C^{j}_{1} and C^{j}_{2}, are chosen so as to maximize a discounted (with discount rate

s_d) *flow of utility* over time (where T can approach infinity):

$$\int_0^T U^j[C^j_1,C^j_2,E^j]*\exp[-s_d t]dt \tag{1}$$

This maximization is subject to conditions representing the system of economic and environmental processes and interactions. These include the following.

Production in region j may be represented as:

$$Q^j = F^j(K^j,E^j,T^j) \tag{2}$$

Accounting equations for distribution of output in regions A and B between investment and consumption of domestic and imported goods are as follows:

$$Q^A = I^A_K + I^A_T + C^A_1 + C^B_1, \tag{3}$$

$$Q^B = I^B_K + C^A_2 + C^B_2, \tag{4}$$

Capital accumulation and depreciation is a standard equation, where investment is considered a regional activity, and is restricted from above by regional production.

$$dK^j/dt = I^j_K - \delta^j_K*K^j \tag{5}$$

Investment in technological innovation in region A is represented as:

$$dT^A/dt = I^A_T - \delta^A_T*T^A \tag{6}$$

Diffusion of technological innovation to region B, with some time delay equal to d, is:

$$T^B(t) = T^A(t-d) \tag{7}$$

Regional environmental dynamics are either linear (e=0) or logistic (e=1) functions with a carrying capacity M^j and possibly based on interactions between the regional environments (dum=0) or not (dum=1). *Negative impacts of the economy on the environment* are included via the last term, based on waste per unit of output w^j, decreasing in the state of technology T^j, and output Q^j.

$$dE^j/dt = r^j*(\text{dum } E^j + (1-\text{dum})*\text{Sqrt}[E^A*E^B])*(1-e*E^j/M^j) - w^j(T^j)*Q^j \tag{8}$$

And finally the following *initial conditions* apply:

$$K^j(0)=K^j_0,\ T^j(0)=T_0,\ E^j(0)=E^j_0. \tag{9}$$

Note that all variables have a time index and are non-negative.

To complete the non-coordination model, one may assume that for region A E^B and C^A_2, and for region B, E^A, T^A and C^B_1 are exogenous, reflecting a limited potential for control of regions. The two region-specific commodities considered are assumed to be different and essential in the utility function. In other words, there is complete specialization, so as not to complicate the model too much (one of the unavoidable heroic assumptions). This implies that there will be trade between regions. The *interregional trade* occurs via the following two market behaviour conditions (i.e. optimal utility conditions):

$$C^A_2 * U^A_2 = C^B_1 * U^A_1 \tag{10}$$

$$U^A_1 / U^A_2 = U^B_1 U^B_2 \tag{11}$$

The coordination problem

Here the objective function is for simplicity considered as the discounted flow of the sum of unweighted utilities of the two regions.

$$\int_0^T \{U^A[C^A_1,C^A_2,E^A] + U^B[C^B_1,C^B_2,E^B]\}*\exp[-s_d t]dt \tag{12}$$

subject to (2)- (8), since all variables are endogenous now.

For an elaboration of this optimization problem we refer to the annex. Comparing the optimality conditions for the coordination and non-coordination cases, the following remarks are in order:

- Under coordination the rate of growth will be slower when the environmental externalities dominate the technological externalities, and vice versa.
- Multiregional externalities may imply unsustainability for the global system and each region; regional sustainability without global sustainability is not possible.
- Perfectly symmetric regions may imply multiple equilibria; non-linear environmental processes may imply absence of an equilibrium.
- Technological positive externalities require coordination investment policies regarding technological diffusion.
- Coordination of what growth/investment policy ? trade policy? environmental policy?
- No coordination may imply free rider benefits which are increasing over time, until the global-regional feedbacks become excessive.

5. A numerical example

It may be interesting to consider a dynamic descriptive counterpart of the model presented in the previous section, which focuses on the structure of the model conditions, and not on optimality from a social perspective. There are then more degrees of freedom. The assumption is then that investment is not chosen to optimize some objective - along with other controls - but that it is examined how ex-ante (or intrinsic) growth of man-made production factors results via environmental feedback in ex-post effective growth of consumption and welfare. The question is thus not what determines growth, but what is the long term environmental impact of a positive rate of growth, given that there exist mechanisms of technological progress and diffusion, consumption and international trade, and interaction between global and regional environmental quality.

The different parts of the model are presented below (i denotes region i; i=A,B) in so far as they differ or are more specific than the general model formulated in the previous section (see for more details on the model of this section van den Bergh and Nijkamp (1995). The functional specifications and numerical values adopted here are just illustrative, hopefully reflecting as much as possible choices in a range consistent with empirical variations.

Each region uses two regional inputs to produce output Q^i according to a Cobb-Douglas type of production function. The regional environment is one input (E^i). The environmental inputs are externalities, as they cannot be directly chosen or influenced by the producers.

$$Q^A = S^A*(K^A)^{a1}*(E^A)^{b1}, \tag{13}$$

$$Q^B = S^B*(K^B)^{a2}*(E^B)^{b2}, \tag{14}$$

where $a_1+a_2 \leq 1$. The technology impact as noted in equation (2) will be included via resource use equations later on.

In order to allow for endogenous formation of trade patterns, regional production prices (P^j) are determined per unit of output, based on the costs of the two inputs. The price of capital $pK_{Kj}=1$ (numeraire) and the price of resource materials (R^j) is p_{Rj}, depending on environmental taxation (exogenous). The unit cost price condition for the commodity price P^j, based on the assumption of constant returns to scale production, is as follows.

$$P^jQ^j = p_{Kj}*K^j + p_{Rj}*R^j. \tag{15}$$

The demand trade system is in reduced form:

$$C^A_2 = P^A*(Q^A - I^A_K - I^A_T)/(v*P^A + P^B), \tag{16}$$

$$C^A_1 = v*C^A_2, \tag{17}$$

$$C^B_1 = P^B*C^A_2/P^A, \tag{18}$$

$$C^B_2 = Q^B - I^B_K - C^A_2. \tag{19}$$

It is assumed here that the value of imports equals that of export, while the terms of trade is endogenous. Furthermore, prices clear commodity markets and capital investment equal savings. These are features of an equilibrium model. In addition, resource supply is not explicitly modelled as a market, but instead it is assumed to have an exogenous (and possibly fixed) price. This can be regarded to include its public good nature - either as a strict physical resource or environmental resource like clean water or good soil quality. Alternatively, one may regard this as either reflecting a large absolute resource supply - focusing on pollution problems - or as a relatively small demand, when only part of the world is modelled. Whatever interpretation, it implies that a kind of disequilibrium approach, with strong equilibrium features is adopted. It should be noted that consumption and production are not the outcome of optimization of utility and profits. Instead, the model is fuelled by scenarios that drive investments, which in turn - together with the trade model and the "memory" for capital and environmental quality - determine the consumption of each good for both regions. These features are characteristic for a macro disequilibrium approach, casted now in an environmental context.

A large value of v refers to a more closed system, a small one (<2) means a very open system, 1 means that imports equal domestic consumption. The fixed value of v, although not realistic perhaps for all countries, can be motivated for many countries by observing historical patterns. As the specific value is not important, v is set equal to 2 here.

Technological progress reaches region B through diffusion (T^B) with a certain time delay. This is set equal to 4 periods since its value is not essential, only that there is such a phenomenon. The parameter dr is a dummy variable indicating the rate of diffusion. Because of the time delay a historical pattern is necessary as an initial condition.

$$T^B(t) = dr\ T^A(t-4), \quad T^B(s)=0, s=1,2,3. \tag{20}$$

The development of technology allows for more efficient resource use in production with an upper limit, given an monotonically increasing function f_{Rj} as follows.

$$R^A = f_{RA}(Q^A)*((T^A + 100)/(4\ T^A + 100)), \tag{21}$$

$$R^B = f_{RB}(Q^B)*((T^B + 100)/(4\ T^B + 100)). \tag{22}$$

The limit of the right hand sides (for very large value of technology indicators) is $0.25*f_{Ri}$ (i=A or B), which indicates a maximum improvement (limit) of 400 % relative to the initial period. This may be regarded as reflecting thermodynamic limitations.

The local environmental quality in each region is described by a logistic growth curve. The carrying capacity (C_c) is assumed constant (set equal to 180). The intrinsic regeneration (growth) rate of the renewable environment (r(.)) is positively related to a global environment index (E_{glob}). Resource extraction in region j (R^j) causes the environmental quality in the region to decline.

$$dE^j/dt = r(E_{glob})*E^j(1-E^j/C_c) - R^j,\ \ E^j(0) = 100 \tag{23}$$

$$r(E_{glob}) = MIN(E_{glob}/C_c,1)*.2 \tag{24}$$

The E_{glob} index represents the quality of the global environment, which is obtained by summing additive and multiplicative aggregation functions of the regional environmental indicators[1]. The aim is here to capture at least two effects. First, when only one region has a low environmental quality, this has severe implications for the global environment. Second, only when both regions collapse, the global environment will do so.

$$E_{glob} = 0.5(E^A*E^B)^{.5} + .5*(E^A+E^B) \tag{25}$$

Finally, welfare is calculated for each region, based on the consumption of each commodity, regional environmental quality, and the state of the global environment.

$$U^j = (C^j_1)^{.6}*(C^j_2)^{.6}*(E^j)^{.4}*(E_{glob})^{.2} \tag{26}$$

In simulation experiments one can investigate the implications of different scenarios. The above model allows for a great number of scenarios to be studied. Each of these represents then a specific combinations of values for all parameter and initial state variables. Recognizing this large potential of choices, several scenarios can be considered. For illustrative purposes we focus here on a symmetric economic system, i.e. identical production functions for both regional economies: $a_i=b_i=0.5$, i=1,2. Furthermore, the ex ante net growth is assumed to equals 3%: g=0.03, and positive outlays on research and development: $I^A_T=5$. Figures 3 to 6 show some results.

With fixed investment in environmental technology in region A, interregional differential impacts are found in our spatial economic system. Figure 3 shows that this strategy has positive impacts on the production in region A relative to region B. Considering Figure 4, one can observe that the environmental quality in region A is improving relative to region B. The global environment is a sort of average, and improves initially. However, the environment in region B would be worse off without region A investing in technological innovation. Because of the technology strategy in region A, its initial welfare is lower than in region B, as is shown in Figure 5. However, after time period 12 the positions are reversed, and a maximum difference is reached in time period 38. Finally, Figure 6 shows that the trade pattern is

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[1] It is noted that this should not be confused with taking averages of the two terms (which is just as arbitrary as any other specification). As one referee remarked, there are three additive terms so that the coefficients sum up to 1.5. For the qualitative character of the results it does not matter much whether this or a slightly different specification is used.

asymmetric and irregular. Domestic consumption of commodity 2 in region B (C^B_2) is decreasing from time 0 on, and is substituted by importing commodity 1 (C^B_1). This is the consequence of changes in relative prices of the commodities. In region A the domestic consumption of commodity 1 (C_{11}) can increase because of the relatively favourable development of environmental quality, acting as a comparative advantage, while the moderately increasing import of commodity 2 (C^A_2) is the net result of the sharp increase of buying power of region A and the increase in the relative price of commodity 2.

[INSERT Figure 3. Capital and production]

[INSERT Figure 4. Regional and global environmental quality]

[INSERT Figure 5. Regional welfare indexes]

[INSERT Figure 6. Consumption and trade]

These results are just exemplatory, aiming to give a flavour of what dynamic patterns one can obtain with a numerically specified descriptive model of growth, trade and environment.

6. Conclusions

The models in Sections 4 and 5 are illustrative of the type of questions to be addressed in the context of spatial sustainable economic development, based on the use of formal modelling procedures. The aim was, rather than to show doomsday or optimistic scenarios - which can never be tested anyway - to show the impact of spatial disaggregation and trade in the context of economic growth, given technological progress and diffusion, and environmental taxation. Many issues have not been dealt with yet, but can in principle be included in the simulation approach, though not so easily in the optimization approach. This is also indicated by the lack of literature on completely specified (and solved) optimal optimal equilibrium growth models with a spatially disaggregated economy and environment. Clearly, introducing such a multi-regional setting in an already complicated dynamic optimization framework leads to an enormous increase of complexity. It should be noted that choosing a social evaluation criterion is more complicated here than in a non-spatial setting, which is caused by the fact that one has to undertake then also an aggregation of regional welfare into some measure of multiregional social welfare. Theoretical generalizations would of course still be useful, but these are - like the two-sector models in standard growth theory - a difficult topic for analytical treatment.

Giving more attention to spatial processes can involve explicit treatment of the link between trade, transport and environment. Dealing with heterogeneity of regions can involve asymmetric versus symmetric characteristics, or developed versus developing countries. Asymmetry may result from unique regional production structure, growth capacity, natural resource endowments, environmental resilience, preferences, and initial levels of physical capital, technology and human capital. Finally, multi-dimensional elaborations do not seem immediately necessary for increasing our understanding of spatial sustainability, as the potential to learn from two-region studies is clearly not yet exhausted.

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Figure 3. Capital and production.
1=K^A, 2=K^B, 3=Q^A, 4=Q^B.

Figure 4. Regional and global environmental quality.
1=E^A, 2=E^B, 3=E_{glob}.

Figure 5. Regional welfare indexes.
1=U^A, 2=U^B.

Figure 6. Consumption and trade.
1=C^A_1, 2=C^A_2, 3=C^B_1, 4=C^B_2.

Annex 1. Optimal coordination problem

The problem is mathematically one of optimal control. A current value Hamiltonian was formulated after resubstituting the equations 2-8. The following conditions resulted next (with partial derivatives of functions indicated by subindexes):

Dynamic equations for costate variables l^{j}_{i} (related to state variables i^{j}; $i=K,T,E$; j refers to the region, $j=A,B$),

$dl^{A}_{K}/dt = -[\ lAK*(FAK-\delta^{A}_{K}) - l^{A}_{E}*w_{A}*F^{A}_{K}\ ]$

$dl^{A}_{T}/dt = -[\ l^{A}_{K}*F^{A}_{T}-l^{A}_{T}*\delta^{A}_{T} - l^{A}_{E}*(w^{A}_{T}*F^{A}+w^{A}*F^{A}_{T}) + l^{B}_{K}*F^{B}_{T} - l^{B}_{E}*(w^{B}_{T}*FB+w^{B}*F^{B}_{T})\ ]$

$dl^{A}_{E}/dt = -[\ U^{A}_{E} + l^{A}_{K}*F^{A}_{E} + l^{A}_{E}*(rA*(dum+(1-dum)*0.5*Sqrt[E^{B}/E^{A}])*(1-e*E^{A}/M^{A}) -$
$r^{A}(e/M^{A})*(dum*E^{A}+(1-dum)*Sqrt[E^{A}*E^{B}]) - w^{A}*F^{A}_{E}) + l^{B}_{E}*(r^{B}*(1-dum)*0.5*Sqrt[E^{B}/E^{A}]$
$*(1-e*E^{B}/M^{B}))\ ]$

$dl^{B}_{K}/dt= -[\ l^{B}_{K}*(F^{B}_{K}-\delta^{B}_{K}) - l^{B}_{E}*w^{B}*F^{B}_{K}\ ]$

$dl^{B}_{E}/dt = [\ U^{B}_{E} + l^{A}_{E}*r^{A}*(1-dum)*0.5*Sqrt[E^{A}/E^{B}]*(1-e*E^{A}/M^{A}) + l^{B}_{K}*F^{B}_{E}$
$+ l^{B}_{E}*(rB*(dum+(1-dum)*0.5*Sqrt[E^{A}/E^{B}])*(1-e*E^{B}/M^{B}) - r^{B}*(e/M^{B})*(dum*E^{B} + (1-dum)$
$Sqrt[E^{A}*E^{B}]) - w^{B}*F^{B}_{E})\ ]$

Optimality conditions,

$l^{A}_{K} - l^{A}_{T} = 0$
$l^{A}_{K} - U^{A}_{1} = 0$
$l^{B}_{K} - U^{A}_{2} = 0$
$l^{A}_{K} - U^{B}_{1} = 0$
$l^{B}_{K} - U^{B}_{2} = 0$

Total derivation w.r.t. time t of these optimality conditions lead then to:
$dl^{A}_{K}/dt = dl^{A}_{T}/dt$
$dl^{A}_{K}/dt = U^{A}_{11}*dC^{A}_{1}/dt + U^{A}_{12}*dC^{A}_{2}/dt + U^{A}_{13}*dE^{A}/dt$
$dl^{B}_{K}/dt = U^{A}_{21}*dC^{A}_{1}/dt + U^{A}_{22}*dC^{A}_{2}/dt + U^{A}_{23}*dE^{A}/dt$
$dl^{A}_{K}/dt = U^{B}_{11}*dC^{B}_{1}/dt + U^{B}_{12}*dC^{B}_{2}/dt + U^{B}_{13}*dE^{B}/dt$
$dl^{B}_{K}/dt = U^{B}_{21}*dC^{B}_{1}/dt + U^{B}_{22}*dC^{B}_{2}/dt + U^{B}_{23}*dE^{B}/dt$

From these and the co-state conditions the following expression is derived,

$l^{B}_{E} = -((\ (-\delta^{A}_{K}+\delta^{A}_{T}+F^{A}_{K}-F^{A}_{T})*U^{A}_{1} - F^{B}_{T}*U^{A}_{2} - F^{A}_{K}*l^{A}_{E}*w^{A} + l^{A}_{E}*(F^{A}_{T}*w^{A}+F^{A}*w^{A}_{T}))\ /(F^{B}_{T}*w^{B} +$
$F^{B}*w^{B}_{T}\ ))$

Total derivation w.r.t time t gives,

$$\begin{aligned}
&dl^{B}_{E}/dt = -(w^{B}_{TT}*F^{B}_{T}*dT^{A}/dt + w^{B}_{T}*(F^{B}_{K}*dK^{B}/dt+F^{B}_{T}*dT^{A}/dt+F^{B}_{E}*dE^{B}/dt) + w^{B}_{T}*F^{B}*dT^{A}/dt + \\
&w^{B}*(F^{B}_{TK}*dK^{B}+F^{B}_{TT}*dT^{A}/dt+F^{B}_{TE}*dE^{B}/dt))*(U^{A}_{1}*(F^{A}_{K}-F^{A}_{T}-\delta^{A}_{K}+\delta^{A}_{T}) - U^{A}_{2}*F^{B}_{T} + \\
&l^{A}_{E}*(-w^{A}*F^{A}_{K}+w^{A}_{T}*F^{A}+w^{A}*F^{A}_{T}))/((w^{B}_{T}*F^{B}+w^{B}*F^{B}_{T})^{2}) + ((U^{A}_{11}*dC^{A}_{1}/dt+U^{A}_{12}*dC^{A}_{2}/dt + \\
&U^{A}_{13}*dE^{A}/dt)*(F^{A}_{K}-F^{A}_{T}-\delta^{A}_{K}-\delta^{A}_{T}) + U^{A}_{1}*((F^{A}_{KK}+F^{A}_{TK})*dK^{A}/dt + (F^{A}_{KT}+F^{A}_{TT})*dT^{A}/dt + \\
&(F^{A}_{KE}+F^{A}_{TE})*dE^{A}/dt) - (U^{A}_{21}*dC^{A}_{1}/dt + U^{A}_{22}*dC^{A}_{2}/dt + U^{A}_{23}*dE^{A}/dt)*F^{B}_{T} - \\
&U^{A}_{2}*(F^{B}_{TK}*dK^{B}/dt+F^{B}_{TT}*dT^{A}/dt+F^{B}_{TE}*dE^{B}/dt) + dl^{A}_{E}*(-w^{A}*F^{A}_{K}+w^{A}_{T}*F^{A}+w^{A}*F^{A}_{T}) + \\
&l^{A}_{E}*((-w^{A}_{T}*F^{A}_{K}+w^{A}_{TT}*F^{A}+w^{A}_{T}*F^{A}_{T})*dT_{A}/dt + (-w^{A}*F^{A}_{KK}+w^{A}_{T}*F^{A}_{K}+w^{A}*F^{A}_{TK})*dK^{A}/dt \\
&+ (-w^{A}*F^{A}_{KT}+w^{A}_{T}*F^{A}_{T}+w^{A}*F^{A}_{TT})*dT^{A}/dt + (-w^{A}*F^{A}_{KE}+w^{A}_{T}*F^{A}_{E}+w^{A}*F^{A}_{TE})*dE^{A}/dt)) / \\
&(w^{B}_{T}*F^{B}+w^{B}*F^{B}_{T})
\end{aligned}$$

The mathematical problem is now such that expressions for changes in the consumption variables are possible. These are extremely tedious expressions, which will not be repeated here. Together with the state variables numerical simulations based on optimal control conditions are in principle possible.