Transboundary Pollution Flows, Capital Mobility and the Emergence of Regional Inequalities

Simon Levin

Department of Ecology and Evolutionary Biology

Princeton University, Princeton,NJ 08540

slevin@eno.Princeton.EDU.

and

Anastasios Xepapadeas

University of Crete, Department of Economics

University Campus, 4100 Rethymno, Greece

E-mail: xepapad@econ.soc.uoc.gr

Version: 22 April

Abstract

The observed relationship between economic development and environmental pollution implies a non-homogeneous spatial pattern between these two characteristics. We consider two similar interacting economies with adverse effects from pollution on capital accumulation. We show that differential flow rates of capital and polluting activities between the two economies can generate spatial patterns which could lead to a spatially heterogeneous steady state, both with respect to capital accumulation and pollution accumulation. Thus there is divergence and not convergence and regional inequalities tend to persist. Policies aiming at balancing the flows of capital and polluting activities might work towards reducing regional inequalities.

Keywords: Spatial heterogeneity, economic development - environmental pollution, environmental Kuznets curve, dispersion relationship, divergence of economies, regional inequalities.

JEL Classification: Q2, O4.

1. INTRODUCTION

The relationship between pollution and growth is an issue that has received considerable attention in recent decades, the central question being whether more growth can mean more or less pollution.[1] The most well-known stylized fact related to this issue is the so-called Environmental Kuznets Curve (EKC), which suggests that environmental pollution increases at early stages of growth, but decreases at higher levels of per capita income.[2] The EKC implies an inverted U or an inverted V relationship between income and environment, which has been analyzed for certain pollutants, in a large number of empirical studies.[3] The econometric studies seem to indicate that the inverted U relationship is more profound for pollutants for which the damage is done in the country where pollution originates.

Many factors have been put forward in the attempt to explain the EKC (Grossman 1994). The fact that the industrialization process entails a shift from agricultural activities to polluting industrial activities suggests that pollution increases in the early stages of development. As development continues, activities shift to relatively cleaner high-tech production and services and environmental quality is expected to improve. During the development process, old capital stock is replaced by

[1] See for example surveys by Smulders (1999), Xepapadeas (2005), Brock and Taylor (2005).

[2] There is a large body of literature regarding the EKC. See, for example, the surveys by Panayotou (2000) Levinson (2002), Dasgupta et al. (2002).

[3] Studies by the World Bank (1992), Grossman and Krueger (1993, 1995) and Selden and Song (1994) suggest that an inverted U relationship exists between ambient environmental quality or emissions for certain types of pollutants, and per capita GDP, wherein after a turning point, emissions decline despite economic development.

new capital stock which embodies environmentally friendly technologies, contributing thus to the improvement of environmental quality as development continuous. The greater demand for cleaner environment in high stages of development induces more stringent environmental policies and improves environmental quality.[4]

Another explanation of the EKC is based on international specialization (Saint-Paul 1994). As international trade grows, countries in a high stage of development import pollution-intensive goods rather than producing them. The countries that produce the pollution-intensive goods are likely to be poor countries whose marginal utility of income is high. This specialization pattern might generate the humped shaped EKC. This argument also points to the relation between the stringency of the environmental policy and the relocation of polluting activities to countries where pollution is less stringent.[5] Lax environmental policy and relocation of polluting activities are associated with the so-called "pollution heaven" hypothesis[6] according to which multinational firms engaging in polluting activities relocate to countries with less stringent environmental regulation. Empirical evidence (Hettige et al. 1990) suggests that a long term upwards trend in industrial emissions both relative to GDP and to manufacturing output is higher among lower-income countries. This result is consistent with an industrial displacement effect of dirty industries as a result of more stringent environmental regulation in industrialized countries since 1970. This evidence could be interpreted as suggesting that in a country or region that has reached a high development stage and where industrialization has led to accumulation of polluting activities and environmental pollution, certain

[4] Ederington et al. (2004) document a substantial shift in US manufacturing towards cleaner industries from 1972-1994.

[5] For example, as noted in Jha and Whalley (2001), a common feature of environmental policy in developing countries, when it exists, is limited compliance and weak enforcement of command and control measures.

[6] See for example, The B.E. Journals in Economic Analysis & Policy, (2004).

mechanisms could go into effect that might cause transport of polluting activities to less-developed regions, where industrialization is not heavy, environmental regulation is relatively less stringent, and polluting activities and pollution accumulation might be less relative to those of the industrialized/developed region. This transport or relocation of polluting activities will induce a corresponding transport of pollution from the developed region to the less developed region.

This interpretation of the EKC implies a non-homogeneous spatial pattern for development and pollution, in the sense that in certain countries or geographical regions we might observe higher development with better environmental quality relative to other countries or regions, as a result of the process described above. The mechanism driving this spatial heterogeneity, and the question of whether this heterogeneity increases or decreases over time as globalization forces tend to work towards closer integration, might be important for understanding regional inequalities with respect to development and environmental quality, and for formulating policies to eliminate them.

In the present paper we seek to explain the emergence of spatial heterogeneity regarding development and pollution on the basis of interactions between economies. These interactions are associated with the movement of capital and polluting activities from the one economy to the other, and they are characterized by negative effects of pollution accumulated through polluting activities in a country, on domestic capital accumulation.

Our methodological approach seeks to capture, as a factor explaining spatially heterogeneous patterns of development and environmental quality, current tendencies towards increased integration on a global scale which induce movements among countries or regions of both capital and, through relocation and industrial displacement, polluting activities that induce pollution flows. We model flows of capital and polluting activities by a simple dynamical model consisting of an equation describing capital accumulation and an equation describing pollution accumulation in each country. The capital accumulation equation is formulated along the lines of a fixed-savings-ratio Solow type model, augmented to account for capital flows and negative effects from pollution, while the pollution accumulation equation describes the accumulation and the diffusion of polluting activities between countries or regions.

We show that if there are substantial differences in the rates of flow of capital and polluting activities (or equivalently pollution), spatial heterogeneity emerges even between two economies with identical fundamental structure. On the other hand, if the rates flow are similar, a spatially homogeneous pattern prevails and the economies converge to the same steady state regarding capital and pollution even if they start from different initial conditions.

These results can be interpreted as suggesting that the neoclassical convergence hypothesis might not hold under differential rates of flow of capital and polluting activities among countries of the same fundamental structure. In fact, under differential flow rates, economies starting close to each other might tend to diverge from each other and converge to different steady states. In this respect, observed regional inequalities regarding development and environmental quality might be a permanent rather than a transient phenomenon. On the other hand, policies directed towards reducing the differential flow rates, and in particular towards increasing the flow of capital and reducing the flow of polluting activities, tend to make the economies converge to a common steady state and eliminate regional inequalities.

2. CAPITAL ACCUMULATION AND CAPITAL DIFFUSION

We consider two similar economies, one located in the north (denoted by N) and the other located in the south (denoted by S). Let $K_j(t)$, $j = N, S$ denote the stock of capital at time $t > 0$ in each economy. We adopt the "behaviorist" tradition (Solow 1956) that savings-investment is a given fraction s of income-output. In this context, the evolution of the stock of capital in the north and in the south is determined by:

$$\frac{dK_N(t)}{dt} = sY_N(t) - \delta K_N(t) + D_K[K_S(t) - K_N(t)] \quad (1)$$

$$\frac{dK_S(t)}{dt} = sY_S(t) - \delta K_S(t) + D_K[K_N(t) - K_S(t)] \quad (2)$$

where δ is the depreciation rate, population is assumed constant, and D_K is the diffusion coefficient characterizing the movement of capital from one economy to the other.[7] For the production part we follow Frankel (1962) to assume that in each economy there are a large number of firms, where each firm faces the same Cobb-Douglas technology and the same factor prices and thus hires factors in the same proportion. In this case the aggregate production function will have the same form as the production function of each firm. In this case the aggregate production function is defined as:[8]

$$Y_j = \bar{A}_j f(K_j), \; f(K_j) = K_j^{\alpha}, \; 0, \alpha \in (0,1) \;\; , j = N, S \quad (3)$$

[7] There is a conservation principle at work in the "diffusion" term so we are dealing with total amounts, that is concentration times area.

[8] To simplify things we assume that labour input is fixed and normalized to one.

Capital K is defined broadly to include human capital and $\bar{A} > 0$ is a scale factor that reflects the level of technology. In this model we assume that the scale factor is a function of aggregate capital, or $\bar{A}_j = A(K_j)$ with $A^{'}(K_j) > 0$.[9] On the other hand, the function $f(K_j)$ $j = N, S$ has the following properties:

$$\begin{aligned} f^{'}(K_j) &> 0,\ f^{''}(K_j) < 0 \\ \lim_{K_j \to \infty} f^{'}(K_j) &= 0\ ,\quad \lim_{K_j \to 0} f^{'}(K_j) = \infty \end{aligned}$$

The first property reflects positive marginal productivity and diminishing returns to capital, while the second expresses the familiar Inada conditions.[10] Thus, in our model the production function (3) satisfies the Inada conditions for the $f(K)$ part but not for the whole function.

The aggregate production function, common to both regions (economies), is specified as:

$$Y = A(K)\, K^{\alpha},\ 0 < \alpha < 1$$

Using the Frankel-Romer formulation for the scale factor we have $A(K) = AK^{\beta}$, so that $Y = AK^{\alpha+\beta}$.[11] If $\alpha + \beta \geq 1$, then the Inada condition is violated for the whole production function, since

$$F_K = \partial Y / \partial K = (\alpha + \beta)\, AK^{\alpha+\beta-1} \tag{4}$$

[9] This assumption was first used by Frankel (1962), where it was assumed that the scale factor was a function of the capital/labor ratio or $A(K/L)^{\beta}$ .This assumption has also been used by Romer (1986). See also Aghion and Howitt (1998, pp. 25-29).

[10] As is well known, most of the current generation of growth models - the endogenous growth models - violate this Inada condition in order to generate perpetual growth at positive rates without the need to assume exogenous technical change.

[11] The same formulation can be obtained if we consider a learning-by-doing model (Arrow 1962). The production function can be written as $Y = K^{a}[AL]^{1-a}$, where A is knowledge, which grows with aggregate capital according to the learning-by-doing assumption. Knowledge is related to aggregate capital by the power function $A = BK^{\phi}, \phi > 0$. Then $Y = AK^{a+\beta}$, $A = (BL)^{1-a}$, $\beta = \phi(1 - a)$ (Romer 2001, Chapter 3).

In particular, if $\alpha + \beta = 1$, we have constant social returns to capital and the usual AK model.

In a spatially homogenous model where $D_K = 0$ and s and δ are fixed, the growth equation becomes

$$\dot{K} = sAK^{\alpha+\beta} - \delta K$$

If $\alpha + \beta = 1$ and provided that $sA > \delta$, then the economy grows at a fixed positive growth rate $g = \dot{K}/K = sA - \delta$. If $\alpha + \beta > 1$ then we have increasing social returns to capital and growth will accelerate indefinitely.

3. POLLUTION ACCUMULATION AND POLLUTION DIFFUSION

In each region polluting activities contribute to aggregate emissions $e(t)$, defined as $e(t) = vY_j(t)$, $j = N, S$ where v denotes emissions per unit of output,[12] and pollution accumulation is denoted by $P_j(t)$. Let the region N be industrialized at a higher development stage relative to S and let its total accumulated pollution be higher than the accumulated pollution in the south. We assume that polluting activities move from the region of higher development and higher accumulated pollution to the region of lower development and pollution as a result of international specialization and the industrial displacement effect of dirty industries discussed in the Introduction. We assume that this transport of polluting activities induces a pollution flow which is proportional to the difference of the accumulated pollution in the two regions, or $D_P [P_S(t) - P_N(t)]$. This underlies the assumption that if economies are very similar regarding pollution accumulation, there will be little room for transport of polluting activities from one to the other. Under these

[12] The emission coefficient in a more sophisticated model could be defined as $v(K_j)$, where $v(K_j)$ is a non-increasing function of K_j, indicating that as capital accumulates relatively "cleaner" techniques are used.

assumptions the evolution of the pollution stock in each economy is determined by:

$$\frac{dP_N(t)}{dt} = vY_N(t) - \gamma P_N(t) + D_P[P_S(t) - P_N(t)] \quad (5)$$

$$\frac{dP_S(t)}{dt} = vY_S(t) - \gamma P_S(t) + D_P[P_N(t) - P_S(t)] \quad (6)$$

where D_P is the diffusion coefficient characterizing the movement of pollution from one region to the other, and γ is a natural pollution depreciation rate. In our model the economy feeds pollution accumulation through capital accumulation. The pollution module of the model is linked to the economy by assuming that pollution is detrimental to human capital. This assumption (Gradus and Smulders 1993) underlies the idea that pollution, in the form of air pollution, smog and heavy metals, increases the depreciation rate of human capital due to health effects. In this case the depreciation rate of capital can be written as

$$\delta \equiv \delta(P_j(t)), \ \frac{\partial \delta}{\partial P_j} > 0, \ j = N, S$$

and the growth equations for north and south become

$$\frac{dK_N(t)}{dt} = sY_N(t) - \delta(P_N(t))K_N(t) + D_K[K_S(t) - K_N(t)] \quad (7)$$

$$\frac{dK_S(t)}{dt} = sY_S(t) - \delta(P_S(t))K_S(t) + D_K[K_N(t) - K_S(t)] \quad (8)$$

Thus the effect of pollution can override the stimulatory effects of capital inflows.

The system of (5), (6), (7) and (8) determines the evolution of the capital stock and the pollution stock in each economy.

4. STEADY STATE EQUILIBRIUM WITHOUT DIFFUSION

If there is no diffusion, that is no transport of capital or polluting activities, then a steady-state equilibrium in north and south is defined as:

$$\left(\overline{P}_j, \overline{K_j}\right) \quad : \quad \frac{dP_j}{dt} = \frac{dK_j}{dt} = 0 \text{ or} \tag{9}$$

$$0 \quad = \quad v\overline{Y}_j - \gamma\overline{P}_j \ , \ 0 = s\overline{Y}_j - \delta\left(\overline{P}_j\right)\overline{K}_j, \ j = N, S \tag{10}$$

$$\overline{P}_N \quad = \quad \overline{P}_S = \overline{P} \ , \ \overline{K}_N = \overline{K}_S = \overline{K} \tag{11}$$

To examine the stability properties of the spatially independent steady state, we form the linearization matrix around the steady state, which is defined as

$$J = \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} -\gamma & (\alpha+\beta)\, vA\overline{K}^{a+\beta-1} \\ -\delta'\left(\overline{P}\right)\overline{K} & (\alpha+\beta-1)\,\delta\left(\overline{P}\right)/\overline{K} \end{pmatrix}, j = N, S \tag{12}$$

From our assumptions we have that at a positive steady state $a < 0$, $b > 0$, $c < 0$, $d > 0$.

This steady state is stable provided the eigenvalues of J have negative real parts; that is, $\mathrm{tr}(J) = a + d < 0$ and $\det(J) = ad - bc > 0$. For $\mathrm{tr}(J) < 0$ to hold, γ should be sufficiently high and $(a + \beta)$ should be sufficiently close to unity; that is, we should not have very strong increasing returns. Henceforth we assume that the steady state is stable.

Thus, without diffusion, both north and south converge to a stable long-run capital stock and pollution stock equilibrium. This steady state is spatially homogeneous, since independent of initial conditions both economies (which have the same structure) converge to the same steady state. This result can be regarded as an extension of the neoclassical convergence result to the convergence of both capital and pollution to a stable steady state.

It is also interesting to note that the inhibitory effect of pollution on capital accumulation and output production prevents sustained growth, which would have been the case in a model with increasing returns to capital and capital depreciation independent of the pollution stock, or $\delta(P) \equiv \delta$.

5. TRANSPORTATION OF POLLUTING ACTIVITIES, CAPITAL MOBILITY, AND SPATIAL PATTERN FORMATION

To analyze the effects of capital flows and pollution flows between the two economies, we consider whether small perturbation caused by diffusion, that is transport of polluting activities and capital mobility between the two regions, can destabilize the spatially homogeneous steady state. In this we extend the classical arguments of Turing (1952), and standard methods (Murray 1993). We consider therefore the linearization matrix of the system (5), (6), (7) and (8), around the spatially homogeneous steady state $\left(\overline{P}_N, \overline{K}_N, \overline{P}_S, \overline{K}_S\right) = \left(\overline{P}, \overline{K}, \overline{P}, \overline{K}\right)$ .The linearization matrix is defined as:

$$M = \begin{pmatrix} a - D_p & b & D_P & 0 \\ c & d - D_K & 0 & D_K \\ D_P & 0 & a - D_p & b \\ 0 & D_K & c & d - D_K \end{pmatrix} \tag{13}$$

Using results from tensor calculus (see Levin 1974) we can easily show that the eigenvalues of M are those of $A = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$, plus those of the matrix

$$S = A - 2B = \begin{pmatrix} a - 2D_P & b \\ c & d - 2D_K \end{pmatrix}, B = \begin{pmatrix} D_P & 0 \\ 0 & D_K \end{pmatrix} \tag{14}$$

Since we have already assumed that A is a stability matrix, it follows that capital flows and pollution diffusion between the two countries can destabilize the spatially homogenous steady state if

$$\begin{aligned} \det(S) &= (a - 2D_P)(d - 2D_K) - bc < 0 \\ a &< 0, d > 0, bc < 0 \end{aligned} \tag{15}$$

with (a, b, c, d) evaluated at the spatially uniform steady state. If destabilization occurs, then the spatially dependent steady state is a saddle point.

To examine conditions under which (15) is satisfied, we assume that $D_p = k^2 D_K$. Then (15) is satisfied provided that

$$Q(k) = 4k^2 D_K^2 - 2\left(k^2 d + a\right) D_K + (ad - bc) < 0 \tag{16}$$

From (16), we need

$$2k^2 D_K (2D_K - d) < 2aD_K - (ad - bc) \tag{17}$$

Because $a < 0$ and $ad - bc > 0$, this requires

$$D_K < \frac{d}{2} \tag{18}$$

that is the flow rate of capital is bounded by its autocatalytic effect. If (18) is satisfied, (17) becomes equivalent to the condition:

$$k > k_1 \tag{19}$$

where

$$k_1 = \sqrt{\frac{(ad - bc) - 2aD_K}{2D_K\,(d - 2D_K)}} \tag{20}$$

Note that, since $(ad - bc) > 0$ and $a + d < 0$, this guarantees that $k_1 > 1$; that is, the flow rate of pollution must be greater than the flow rate of capital.[13]

Another way to examine regions of instability for (D_P, D_K) combinations, is to solve $\det(S) = 0$ as a function of D_p to obtain

$$D_K = \frac{-(ad - bc) + 2dD_p}{2\,(2D_p - a)} \tag{21}$$

The graph of (21) splits the two-dimensional space into two subspaces. One of the two subspaces is the region of diffusive instability.[14]

If conditions associated with (16) or (21) are satisfied, then small perturbations caused by capital mobility and relocation of polluting activities between the two countries will destabilize the spatially uniform steady state.[15] This implies the

[13] From (20), we have

$$k_1 > \sqrt{-a/\,(d - 2D_K)} > \sqrt{-a/d} > 1$$

[14] The exact shape of the diffusive instability region will be determined in the following section using a numerical example.

[15] Destabilization will be prevented only if the perturbation takes the economies on the stable

initiation of pattern formation in the sense that capital stock, production, and pollution stock will start being different between the two countries. Since the production and emission structure of both countries are the same, pattern formation is induced solely by capital and pollution flows.

Classical theory (Segel and Levin 1976) tells that a spatially heterogeneous steady state will bifurcate from the homogeneous equilibrium, and we expect that the heterogeneous equilibrium will be stable. Segel and Levin established this stability for a slightly different set of nonlinear equations, using successive approximations and multiple time scales. For our system, we turn instead to simulation to demonstrate the effect.

If the spatially non-homogeneous steady-state equilibrium is stable, while the spatially homogeneous steady-state equilibrium is not stable to small perturbation caused by capital and pollution diffusion, then the effects of pollution on capital formation, combined with capital mobility and transboundary pollution, cause regional inequalities. That is, while both regions (countries) converge to the same capital - stock - pollution - stock long-run equilibrium in the absence of transboundary movement of pollution and capital mobility, when these effects are present they converge to *different* capital-stock - pollution-stock combinations in the long-run equilibrium. Thus the combination of transboundary pollution movement and capital mobility could cause regional inequalities. We illustrate this with a numerical example.

5.1. A numerical example

We consider two regions (economies) characterized by the following structure common to both regions:

manifold of the saddle point.

Production Function	AK^{a+b}	$A = 10, a = 0.3, b = 0.8$[16]
Depreciation Function	$P^{1+\delta}$	$\delta = 0.5$[17]
Savings Ratio	s	$s = 0.25$
Emission Coefficient	v	$v = 0.1$
Pollution Depreciation	γ	$\gamma = 0.5$

In the absence of capital mobility and transboundary effects, the spatially homogeneous steady state is the same for both economies and is determined by the solution of the system

$$\begin{aligned} 0 &= sAK^{a+\beta} - KP^{1+\delta} \\ 0 &= vAK^{a+\beta} - \gamma P \end{aligned}$$

The spatially homogeneous steady state is

$$K_N^H = K_S^H = 0.923456 \tag{22}$$

$$P_N^H = P_S^H = 1.83226 \tag{23}$$

The linearization matrix A is

$$A = \begin{pmatrix} -0.5 & 1.09128 \\ -1.875 & 0.248017 \end{pmatrix}, \tag{24}$$

whose eigenvalues have negative real parts

$$\lambda_{1,2}^A = -0.125992 \pm 1.38068i \tag{25}$$

[16] Having $a+b > 1$ reflects the assumption that technology is characterized by increasing returns (see also Cazzavillan, Lloyd-Braga and Pintus 1998).

[17] Since, by being detrimental to human capital, the depreciation functions acts as damage function, we adopt the usual convexity assumption associated with damages.

Thus the spatially homogeneous steady state is stable. The approach to this steady state is shown in figure 1. This figure shows the solutions paths of the system of differential equations

$$\dot{K}_j = sAK_j^{a+\beta} - K_j P_j^{1+\delta} \tag{26}$$

$$\dot{P}_j = vAK_j^{a+\beta} - \gamma P_j \quad , j = N, S \tag{27}$$

with initial conditions $K_N = 1.4$, $K_S = 1, P_N = P_S = 1$. Therefore although the two regions start from different capital stocks, they both converge with oscillations to the spatially homogeneous steady state. This result is in agreement with the neoclassical convergence hypothesis.

[Figure 1]

To examine destabilization of this steady state under diffusion, we use (18) indicating that $D_K < d = 0.248017$, and we set $D_K = 0.1$, and $D_P = k^2 D_K$. Then matrix S becomes

$$S = \begin{pmatrix} -0.5 - 2k^2 D_K & 1.09128 \\ -1.875 & 0.248017 - 2D_K \end{pmatrix} \tag{28}$$

with

$$Q = \det S = 2.02214 - 0.0096034k^2 \tag{29}$$

The dispersion relationship (16) is shown in figure 2.

[Figure 2]

If we choose $k = 20$ so that $Q < 0$, matrix S becomes

$$S = \begin{pmatrix} -80.5 & 1.09128 \\ -1.875 & 0.04817 \end{pmatrix} \tag{30}$$

with eigenvalues

$$\lambda_{1,2}^{S} = (-80.4746, 0.0226061) \tag{31}$$

Matrix M of (13), which is the linearization matrix of the system

$$\dot{P}_N = vAK_N^{a+\beta} - \gamma P_N + D_P\,(P_S - P_N) \tag{32}$$

$$\dot{K}_N = sAK_N^{a+\beta} - K_N P_N^{1+\delta} + D_K\,(K_S - K_N) \tag{33}$$

$$\dot{P}_S = vAK_S^{a+\beta} - \gamma P_S + D_P\,(P_N - P_S) \tag{34}$$

$$\dot{K}_S = sAK_S^{a+\beta} - K_S P_S^{1+\delta} + D_K\,(K_N - K_S) \tag{35}$$

around the spatially homogeneous steady state, is:

$$M = \begin{pmatrix} -40.5 & 1.09128 & 40 & 0 \\ -1.875 & 0.148017 & 0 & 0.1 \\ 40 & 0 & -40.5 & 1.09128 \\ 0 & 0.1 & -1.875 & 0.148017 \end{pmatrix} \tag{36}$$

with eigenvalues[18]

$$\lambda_1^M = -80.4746,\ \lambda_{2,3}^M = -0.125992 \pm 1.38068i \tag{37}$$

$$\lambda_4^M = 0.0226061 \tag{38}$$

[18] The eigenvalues of M are those of A and S.

There is one positive eigenvalue so the spatially homogeneous steady state is not stable under perturbations caused by capital and pollution diffusion, for the specific relationship $D_P = k^2 D_K$ between pollution and capital diffusion. A more general set of (D_P, D_K) is shown in figure 3, which depicts relationship (21) for the specific parameters used in this example. The region of diffusive instability is under the line DD.

[Figure 3]

Since under relocation of polluting activities which induce pollution diffusion, and under capital mobility, the spatially homogeneous steady state is not stable, we examine the properties of the spatially heterogeneous steady state which is obtained as the solution of the system (32)-(35) with $\dot{P}_N = \dot{K}_N = \dot{P}_S = \dot{K}_S = 0$. This steady state is

$$P_N^{HR} = 1.84465 \, , K_N^{HR} = 1.26979 \tag{39}$$

$$P_S^{HR} = 1.8352 \, , K_S^{HR} = 0.570576 \tag{40}$$

The linearization matrix of the spatially heterogeneous steady state is

$$M^{HR} = \begin{pmatrix} -40.5 & 1.12659 & 40 & 0 \\ -2.5869 & 0.211108 & 0 & 0.1 \\ 40 & 0 & -40.5 & 1.03998 \\ 0 & 0.1 & -1.15943 & 0.0138139 \end{pmatrix} \tag{41}$$

with eigenvalues:

$$\lambda_1^{M^{HR}} = -80.4744,\ \lambda_{2,3}^{M^{HR}} = -0.126996 \pm 1.38605i \quad (42)$$

$$\lambda_4^{M^{HR}} = -0.0446666 \quad (43)$$

Thus the spatially heterogeneous steady state is stable. The approach path is shown in figure 4, for the same initial conditions $K_N = 1.4$, $K_S = 1, P_N = P_S = 1$ as in the no-diffusion case.

[Figure 4]

As the results indicate, while in the no-diffusion case the initial inequality was eliminated and both regions were equal with respect to capital stock and pollution stock at the steady state, under diffusion the inequality not only remains, but it is magnified at the steady state. At the steady state there is inequality both with respect to the pollution stock and the capital stock. It should be noticed that the initial deviation between capital stocks has doubled. Thus, while the standard convergence hypothesis of economic theory seems to hold when there is no pollution or capital movements across regions, the same convergence hypothesis could, when pollution and capital move across regional (national) boundaries and under certain conditions, break down and lead to regional inequalities.

6. CONCLUDING REMARKS

The observed relationship between economic development and environmental pollution can be regarded as implying a non-homogeneous spatial pattern between these two characteristics, induced by cross-country differentials in the stringency of environmental policy and displacement of polluting industries during the process of economic development. An open question is whether this spatial heterogeneity tends to increase or not under the influence of globalization forces. If spatial differences regarding the developmental stage and the state of the environment tend to persist over time, this might question some of the assertions of the neoclassical convergence hypothesis.

In this paper we consider two similar interacting economies characterized by Solow type capital accumulation under Frankel-Romer externalities which induce increasing returns, and adverse effects from pollution on capital accumulation. We show that differential flow rates of capital and polluting activities between the two economies not only can generate spatial patterns but that these patterns could lead to a spatially heterogeneous steady state, both with respect to capital accumulation and pollution accumulation. Thus there is divergence and not convergence and regional inequalities tend to persist. It would seem that policies aiming at balancing the flows of capital and polluting activities might work towards convergence both in terms of development and pollution accumulation, hence reducing regional inequalities.

REFERENCES

[1] Aghion, P. and P. Howitt (1998), *Endogenous Growth Theory* (The MIT Press, Cambridge Massachusetts).

[2] Arrow, K., "The economic implications of learning by doing," *Review of Economic Studies*, 29, 1962, 155-173.

[3] The B.E. Journals in Economic Analysis & Policy, (2004), Special Issue on "*The Pollution Haven Hypothesis*", http://www.bepress.com/bejeap/

[4] Brock, W. and M. Scott Taylor, (2003), "Economic Growth and the Environment: Maching the Stylized Facts," *SSRI, University of Wisconsin,* 2003-16.

[5] Cazzavillan, G., Lloyd-Braga, T. and P. Pintus, (1998), "Multiple Steady States and Endogenous Fluctuations with Increasing Returns to Scale in Production, *Journal of Economic Theory,* 80, 60-107.

[6] Dasgupta, S., B. Laplante, H. Wang and D. Wheeler, (2002), "Confronting the Environmental Kuznets Curve", *Journal of Economic Perspectives* 16: 147-168.

[7] Ederington, J. Levinson, A., and J. Minier, (2004) "Trade Liberalization and Pollution Havens", *Advances in Economic Analysis & Policy*: Vol. 4: No. 2, Article 6, http://www.bepress.com/bejeap/advances/vol4/iss2/art6.

[8] Frankel, M. (1962) "The Production Function in Allocation and Growth", *American Economic Review*, 55(3), pp. 296-319.

[9] Grossman, G.M. (1994), "Pollution and Growth: What do we know?," in I. Goldin and L.A. Winters, (Eds), *The Economics of Sustainable Development*, pp. 47-51, Cambridge University Press, Cambridge.

[10] Grossman, G.M. and A.B. Krueger (1993), "Environmental impacts of a North American free trade agreement", in P. Garber, ed., *The U.S.-Mexico Free Trade Agreement* (The MIT Press, Cambridge, Massachusetts).

[11] Grossman, G.M. and A.B. Krueger (1995), "Economic growth and the environment," *The Quarterly Journal of Economics* 110, 353-377.

[12] Gradus, R. and S. Smulders (1993), "The trade-off between environmental care and long-term growth - pollution in three prototype growth models", *Journal of Economics* 58: 25-51.

[13] Hettige, H., R.E.B. Lucas and D. Wheeler (1992), The Toxic Intensity of Industrial Production: Global Patterns, Trends, and Trade Policy', *AEA Papers and Proceedings*, 82 (2), 478-81.

[14] Jha, R. and J.W. Whalley (2001), "The environmental regime in developing countries," in C. Carraro and G. Metcalf (Eds), *Distributional and Behavioural Effects of Environmental Policy: Evidence and Controversies*, NBER, Chicago University Press.

[15] Levin, S.A., (1974), "Dispersion and Population Interactions," *American Naturalist*, 108(960), 207-228.

[16] Levinson, A. (2002), "The ups and downs of the environmental Kuznets curve," in J. List and A. de Zeeuw (Eds.), *Recent Advances in Environmental Economics,* Edward Elgar, Cheltenham.

[17] Murray, J.(1993), *Mathematical Biology*, Second Edition, Berlin, Springer.

[18] Panayotou, T. (2000), "Economic growth and the environment", *CID Working Paper No. 56*, Harvard University.

[19] Romer, D. (2001), *Advanced Macroeconomics,* Second Edition, Mc-Graw Hill, New York.

[20] Turing, A. (1952), "The Chemical Basis of Morphogenesis," *Philosophical Transactions of the Royal Society of London*, *Series B*, 237, pp37-72.

[21] Romer, P.M. (1986), “Increasing Returns and Long-Run Growth”, *Journal of Political Economy*, 94 (5), 1002-37.

[22] Smulders, S. (1999), “Endogenous growth theory and the environment”, in: J. van den Bergh, ed., *The Handbook of Environmental and Resource Economics,* (Edward Elgar Publishers, Cheltenham).

[23] Segel, L.A., and S.A. Levin (1976), “Application of Non Linear Stability Theory to the Study of the Effects of Diffusion on Predator Prey Interactions,” pp 123-152, in *Topics in Statistical mechanics and Biophysics: A Memorial to Julius L. Jackson*, edited by R.A. Piccirelli, New York, American Institute of Physics.

[24] Saint-Paul, G., (1994), “Discussion”, in I. Goldin and L.A. Winters, (Eds), *The Economics of Sustainable Development*, pp. 47-51, Cambridge University Press, Cambridge.

[25] Selden, T.M. and D. Song (1994), Environmental Quality and Development: Is There a Kuznets Curve for Air Pollution Emissions?’, *Journal of Environmental Economics and Management*, 27 (2), 147-62.

[26] Solow, R. (1956), “A contribution to the theory of economic growth”, *Quarterly Journal of Economics* 70: 65-94.

[27] Xepapadeas, A. (2005), “Economic Growth and the Environment,” in the *Handbook of Environmental Economics, Volume 3: Economywide and International Environmental Issues* edited by Karl-Goran Mäler and Jeffery Vincent, a volume in the series Handbooks in Economics, edited by, Kenneth Arrow and Michael D. Intrilligator, Elsevier Publishers,Amsterdam (forthcoming).

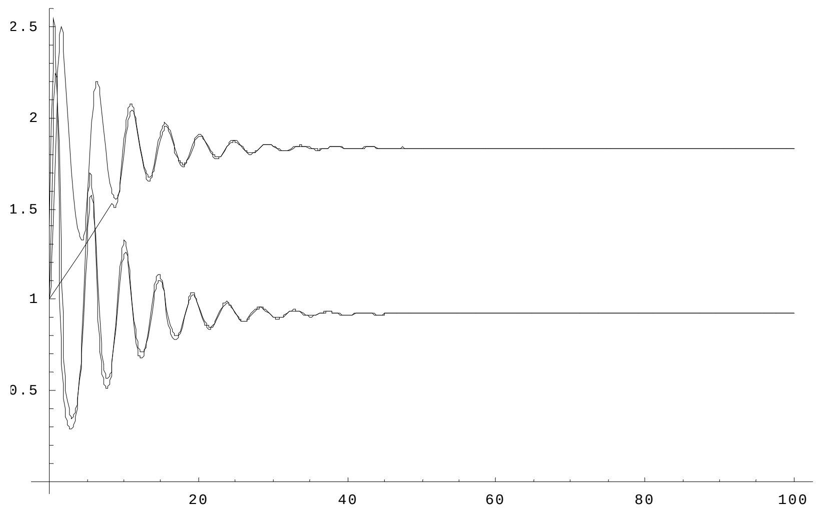

FIG. 1 Convergence to the spatially homogeneous steady state

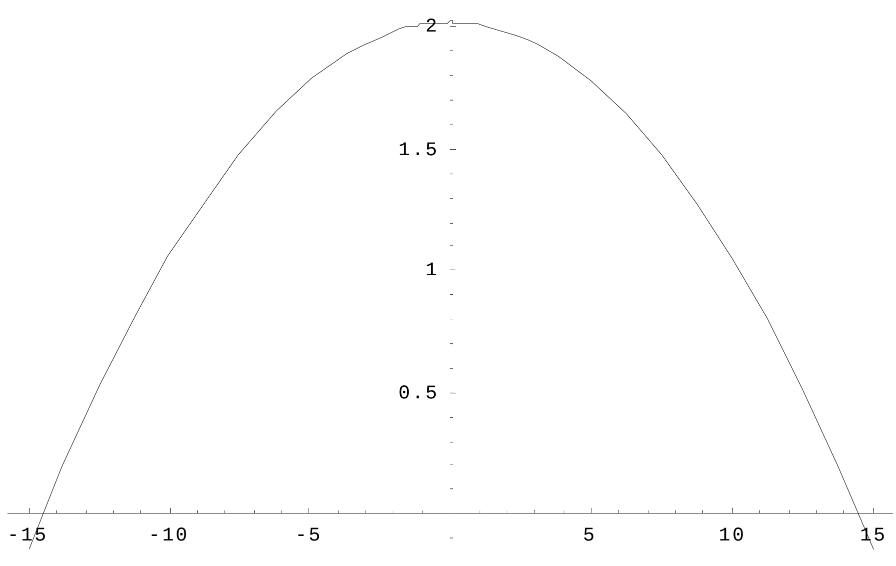

FIG. 2 The dispersal relationship

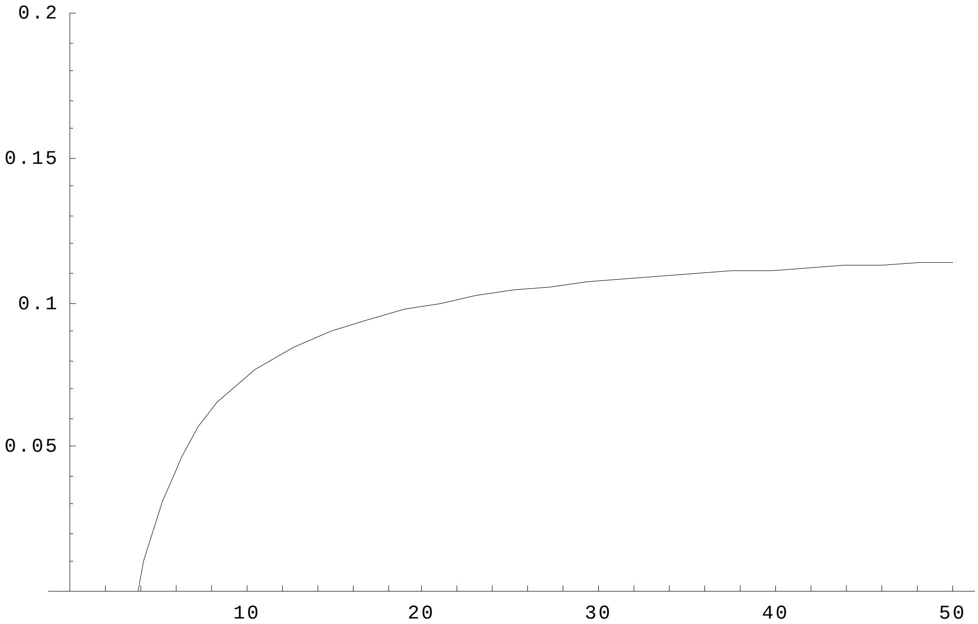

FIG. 3 The region of diffusive instability

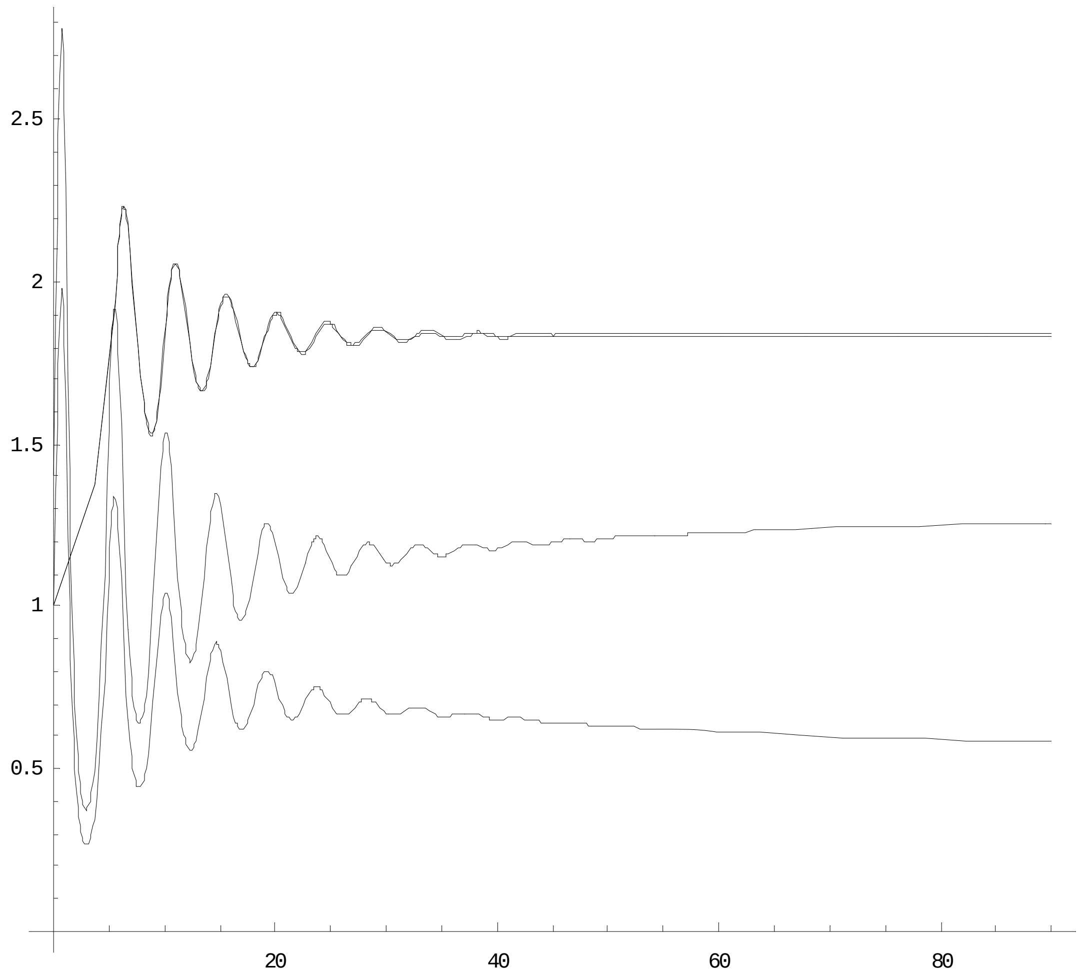

FIG. 4 Convergence to the spatially heterogeneous steady state.