Spatial distribution of economic activities and transboundary pollution

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Abstract

Different empirical studies confirm that individuals consider environmental quality in their location choices. Nonetheless, little attention has been devoted to the role of transboundary pollution in the agglomeration or spreading of economic activities. This contribution introduces transboundary pollution in the field of New Economic Geography providing an extension of Ottaviano's Core-Periphery Model (Ottaviano, 2001). In terms of long run equilibria, the introduction of pollution to the footloose entrepreneur model has two major consequences. First, it allows several original equilibrium configurations, which do not arise by considering only transport costs. Secondly, for a given level of transport cost, different equilibrium configurations may occur, depending on the environmental parameters.

Keywords: Agglomeration; Economic geography; Transboundary pollution; Population mobility.

1 Introduction

The location of industrial activities is at the heart of economic and political issues. In a context where regions are facing global competition, a good understanding of the determinants of the location of economic activities is an important asset for policymakers to improve the attractiveness and competitiveness of their region. While most previous literature addresses this issue by focusing on capital location, a different approach, still untapped, is presented here. This paper studies the spatial distribution of economic activities through the location choices of skilled workers. Indeed, a territory's population of skilled workers represents a stock of human capital which has great significance for the nature and the scope of economic activities. Consequently, skilled workers' migrations, more than others, may cause structural change in the productive system of a territory or induce a spatial redistribution of economic activities. So, the study of the causes of skilled workers' migrations seems to be one of the keys to understanding the spatial distribution of economic activities and should attract more attention in a context where the "environmental" variable impacts many economic agents' decisions. Indeed, while the location of capital is only guided by profit prospects, a skilled worker takes into account, in his choice of location, not only

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monetary factors, such as the wages and price index, but also non-monetary factors, such as environmental quality.

Many empirical studies have shown that households take into account the level of amenities that regions supply in their choice of location. One of the most important studies in this field is that of Blomquist et al. (1988). They use wage and rent differentials to evaluate the implicit price of amenities. These implicit prices allow them to weight the amenities to establish an index of quality of life. Blomquist et al. (1988) take into account climatic, environmental and urban amenities. The construction of this quality of life index shows that amenity differentials are subject to substantial monetary compensation, both in terms of wages and rent. This leads them to conclude that quality of life is of great importance in the location choices of individuals.

Fewer empirical studies have been especially devoted to the impact of environmental quality on location choices. An example is Kahn's contribution (Kahn, 2000). In his econometric study, Kahn shows that the drastic improvement of air quality in Los Angeles and its suburbs between 1980 and 1994 led to a significant acceleration of population growth. Kahn concludes that the air quality has a significant impact on quality of life and therefore on the location choices of individuals. For example, a county that had decreased by 10 the number of days of peak ozone pollution had a population growth rate 7.8% higher than a county where ozone levels had not changed. In addition, this study shows that skilled workers are particularly sensitive to these improvements in air quality. The number of migrants as part of this category almost doubled in San Bernardino County between 1980 and 1994.

Furthermore, the importance of environmental factors seems likely to strengthen over the long run, in the light of the numerous studies that highlight the health risks caused by industrial pollution. This impact may be even stronger at the regional level, where there are low migration costs, such as administrative or language difficulties, or the advantage of not moving far away from the home region.

This contribution focuses on the issue of transboundary pollution. Because of the moving of air masses or layers of water, many pollutants may deposit far away from the location of their emission, causing environmental damage in another region. This damage may impact on households' welfare and could encourage skilled workers to migrate. Recent empirical studies (see, among others, Ilyin et al., 2010 and Shatalov et al., 2010) show that transboundary pollution is an important phenomenon which concerns many types of pollutant, such as heavy metals (mercury, lead, cadmium) or Persistent Organic Pollutants. In addition, this problem seems particularly interesting from a regional perspective, notably regarding the pollution of rivers. Indeed, many urban centers are located on the banks of great rivers. Thus, the water pollution caused in such centers can generate damage in downstream regions.

The aim of this paper is to provide a theoretical analysis of the impact of transboundary pollution on the migration of skilled workers in an inter-regional trade context, using the New Economic Geography (NEG hereafter) framework, specifically a Core-Periphery model. Monopolistic competition in the polluting sector allows us to consider the well-known home market effect. Moreover, this framework enables us to identify the forces generated by both pecuniary and environmental externalities and so to analyze how each of these factors influences location decisions. This paper follows previous contributions which have integrated environmental issues in Core-Periphery models (see Van Marrewijk, 2005, or Lange and Quaas, 2007). However, the model presented in this paper provides an exhaustive presentation of the different configurations of equilibria which can arise in the presence of transboundary pollution. In terms of geographic scale, this model may be a focus on exchanges and trade between two "small" bordering regions, for example, two regions of a European country, or two states of the US. Indeed, migration costs are not considered, which means that the two regions are relatively close to each other and that the whole economy is relatively homogenous from both the cultural and institutional points of view. Furthermore, as mentioned above, transboundary pollution seems more relevant on the regional scale, unlike global pollution where it is more appropriate to treat intercontinental issues. However, the model can also take into account global pollution, as will be seen below, even though it is not the main purpose of the paper. Empirical studies show that, depending on the type of pollutant, the transboundary effect can be more or less strong. On the one hand, for instance, heavy metals emissions cause what can be called "high transboundary pollution": more than half of the emissions will deposit in foreign countries (see Ilyin et al., 2010). This kind of pollutant is emitted, for example, when producing paint or batteries. On the other hand, Persistent Organic Pollutants, in most cases, cause "low transboundary pollution": less than half of the emissions will deposit in foreign countries (see Shatalov et al., 2010). Persistent Organic Pollutants can be emitted by different activities, such as plastic production and the destruction or production of electric devices. These two types of transboundary pollution are considered later. The model presented here introduces local and transboundary industrial pollution in the analytically solved footloose entrepreneur model of Ottaviano (2001) and assumes that mobile skilled workers are subject to indirect utility differentials. The aim of the model is to consider pollution parameters as well as traditional transport costs. Of course, the fact that skilled workers prefer to locate in the less polluted region is a predictable result. However, the interest of the model is to provide an analysis of the power relationship between pecuniary and environmental externalities. From this perspective, the fully analytically resolved model distinguishes this contribution from previous contributions in this part of the literature. In terms of long run equilibria, the introduction of pollution in the footloose entrepreneur model has two major consequences. First, it allows several original equilibrium configurations, which do not arise when only considering transport costs. Secondly, for a given level of transport cost, different equilibrium configurations may occur, depending on the environmental parameters. Two cases are considered. The first one carries the assumption of symmetry generally applied in NEG literature and can be viewed as purely global pollution (e.g., corresponding to climate change issues). Each region sends the same share of its pollution emission to the other region. In this case, stability of the three NEG classic equilibrium configurations remains the most likely situation. In the second case, transboundary pollution is asymmetric. Only one region emits transboundary pollution, the other one emits purely local pollution. In this case, new stable equilibrium configurations are identified, especially partial agglomeration equilibria, for a certain range of parameters. In each case a formal analysis of the introduction of transboundary industrial pollution is provided, determining the stability conditions for low and high transboundary pollution. Normative aspects of transboundary pollution, such as the consequences of environmental policies on the agglomeration of activities, are not considered in this contribution. [See Elbers and Withagen (2004) for a model explaining population dynamics and agglomeration in compliance with environmental policy, in the case denoted below "purely local pollution", and a review of the literature on this subject.] The results show that transboundary pollution can act as a centrifugal or a centripetal force, respectively in the case of low transboundary pollution or high transboundary pollution.

The remainder of this paper is organized as follows. Section 2 presents a brief survey of theoretical studies dealing with transboundary pollution, and previous attempts to introduce pollution in Core–Periphery models. Section 3 is devoted to the presentation of the model and basic results. Section 4 presents a typology of long run equilibria, according to the range of key parameters (transport and pollution costs). Finally, Section 5 concludes.

2 Theoretical related literature

The problem of acid rain in Scandinavian countries caused by emissions in the United Kingdom and in Germany led to the first studies dealing with transboundary pollution in the economic literature. Kaitala et al. (1992) address the issue in the context of a dynamic game between Finland and the western regions of the former USSR. The aim of their work is to estimate the costs and benefits of an emissions abatement policy. Their analysis includes non-cooperative and cooperative cases. The same problem is studied by Mäler and De Zeeuw (1998) as part of a differential game with a pollution stock. These early environmental economics contributions, dealing with transboundary pollution, do not consider the context of international trade and do not address the problem of migration that may be induced by such pollution.

Various studies have dealt with transboundary pollution problems in an international trade framework. One of the most important studies in this field is that of Copeland and Taylor (1999). Although it considers purely local pollution, it is the basis for many extensions taking into account transboundary pollution. They propose an extension of the Ricardian model of comparative advantages. They develop a model with two regions and two sectors: industry and agriculture. The agricultural productivity of a region depends on its environmental capital. Production in the industrial sector induces pollution and reduces the environmental capital of the region. This causes a loss of agricultural productivity. Unteroberdoerster (2001) and Benarroch and Thille (2001) suggest extensions of the model of Copeland and Taylor (1999) considering transboundary pollution. Benarroch and Thille (2001) also deal with cases where regions differ either in size or in the rate of emissions from the neighboring region. Suga (2002) proposes an extension of Benarroch and Thille (2001), considering these two differences simultaneously. These few examples of international trade models taking into account transboundary pollution do not, however, address the issue of migration.

More recently, a few studies have analyzed the relationship between migration and transboundary pollution. Hoel and Shapiro (2003) discuss this relationship, assuming homogeneity and perfect mobility of the population in a static framework. The governments of different regions engage in a game to set their policies. They lead to a socially efficient situation determined by the Nash equilibrium of a non-cooperative game. Hoel and Shapiro (2004) question the assumption of homogeneity of the population, assuming that agents do not all have the same preferences for environmental quality. This assumption of population heterogeneity can lead to an inefficient non-cooperative game. Haavio (2005) challenges the assumption of perfect mobility of the population by integrating migration costs in his analysis. In addition his analysis is placed in a dynamic setting and takes into account pollution stock. Policies are determined by solving a differential game. In this context, Haavio (2005) shows that households' mobility, as well as pollution emissions' mobility, can lead to a tragedy of the commons: over-pollution. Therefore, a centralized policy and international cooperation is needed.

Following these previous contributions, Kondoh (2006) examines the impact of international migration on welfare in the presence of transboundary pollution in an international trade framework in an extension of Copeland and Taylor's model (Copeland and Taylor, 1999). Regions have technical possibilities for reducing pollution. However, the regions do not enjoy the same level of technology in terms of pollution reduction. Kondoh (2007) addresses the "brain drain" problem in an extension of the model of Kondoh (2006). For this, he considers two factors of production: skilled and unskilled labor. He examines the economic impact of the "brain drain" in the presence of transboundary pollution in a context of international trade.

Independently of these contributions that have introduced transboundary pollution issues to their analysis, a few papers have studied the impact of industrial pollution on skilled workers' location choices in a NEG framework. Van Marrewijk (2005) uses Forslid and Ottaviano's footloose entrepreneur model (Forslid and Ottaviano, 2003) as a basis, including environmental damage. In this model, both industrial and traditional sectors emit purely local pollution. Van Marrewijk (2005) shows analytically that, under this assumption, the damage caused by industrial pollution can act as an agglomeration or a spreading force regarding the pollution levels emitted by the two sectors. Another extension of Forslid and Ottaviano (2003) is provided by Lange and Quaas (2007). They show the possibility of stable partial agglomeration equilibria in the presence of industrial environmental pollution. This result is especially interesting from an empirical point of view, because it corresponds to midsized industrial cities that can be observed in reality. Finally, the contribution of Elbers and Withagen (2004) should be mentioned. It extends the Fujita, Krugman and Venables model (Fujita et al., 1999), explaining population dynamics and agglomeration in compliance with environmental policy, when industrial firms emit purely local pollution. Specifically, they address the pollution haven issues, analyzing the impact of environmental policies on the spatial distribution of industrial firms.

Regarding the literature that has dealt with transboundary pollution problems on the one hand, and that has introduced pollution in a NEG framework on the other, it can be noted that an analysis of the transboundary pollution impact on skilled workers' location choices has not been proposed before. Such an analysis is provided in the remainder of this paper in a Core - Periphery model.

3 Model presentation and basic results

A model quite similar to the Ottaviano (2001) Core-Periphery model (C-P hereafter) except for the presence of a pollution flow resulting from production and affecting the instantaneous utility function is developed.

The economy consists of two regions, A and B, sharing a total fixed endowment of unskilled labor $2L$ and skilled labor H. The unskilled labor is geographically immobile and evenly distributed between locations, each hosting L unskilled workers. Skilled workers are mobile between regions. By setting $H = 1$ by choice of units, the share of skilled workers in A, $h \in [0, 1]$, is also the number of skilled workers in A and $1 - h$ is the number of skilled workers in B. The skilled labor wage in location i; $i = \{A, B\}$ is designated by R_i. The two regions have access to the same level of technology and can produce two types of good: a differentiated modern good D and a homogeneous traditional good Y.

The differentiated good is produced in a monopolistic sector under increasing returns to scale using both skilled and unskilled labor. Trade costs in the differentiated good are modeled as iceberg costs $\tau \geq 1$ à la Samuelson (1952). A fixed number of skilled workers is used in the production of differentiated goods, such that the cost function includes a fixed cost for skilled workers and a marginal cost k corresponding to the unskilled workers used in production. The total cost of production of a quantity x_i is finally given by $C(x_i) = gR_i + kx_i$, with $g = 1$.

Increasing returns, differentiated production and the free entry hypothesis imply an equilibrium characterized by a number of firms equal to the number of varieties n_i. Moreover, $g = 1$ induces that the number of firms equals the number of skilled workers: $n_A = h$ and $n_B = 1 - h$.

The traditional good is produced in a perfectly competitive sector under constant returns to scale using unskilled labor as the unique input. Choosing traditional good as *numéraire*, price equal to one, and assuming free trade for this good (no transport costs) and a unit input coefficient equal to one ensures that the unskilled worker wage is also equal to one.

The instantaneous utility flow[1] of an individual agent located in i is a function of three

[1] The functional form used for the damage function is simpler than that used in Lange and Quaas (2007). However we adopt it because the quadratic function is well-behaved and largely used in explicit models and

variables: D_i, Y_i and E_i. These variables are, respectively, the consumed quantities of both goods in i and the flow of pollution located in $i = \{A; B\}$:

$$U_i = \ln\left[\left(\frac{D_i}{\alpha}\right)^{\alpha}\left(\frac{Y_i}{1-\alpha}\right)^{1-\alpha}\right] - \varphi E_i^2 \tag{1}$$

with $\alpha \in]0;1[$ and $\varphi > 0$.

The differentiated good D is a CES aggregate of foreign and local varieties:

$$D_i = \left\{\int_0^{n_i} [d_{ii}(m)]^{\frac{\sigma-1}{\sigma}} dm + \int_0^{n_j} [d_{ji}(m)]^{\frac{\sigma-1}{\sigma}} dm\right\}^{\frac{\sigma-1}{\sigma}} \tag{2}$$

with $d_{ji}(m)$ the consumption in place i of a single variety m produced in place j; $i,j = \{A,B\}$; $\sigma \in]1,+\infty[$ represents the substitution elasticity between any two varieties and the price elasticity of demand for each variety.

For convenience we choose units such that $k = \frac{\sigma-1}{\sigma}$.

As in Elbers and Withagen (2004), the pollution flows generated in $i = \{A,B\}$ from the production of the modern good are directly proportional to labor input and it is assumed that there are no abatement possibilities. So, the pollution flows in i are given by:

$$F_i = \xi n_i; \;\; \xi > 0 \tag{3}$$

The flow of pollution located in i is finally given by:

$$E_i = \xi\left[(1-\beta_i)\, n_i + \beta_j n_j\right] \tag{4}$$

where $(\beta_i, \beta_j) \in [0,1]^2$; $i = \{A,B\}$; $j = \{A,B\}$; $i \neq j$; is the share of pollution flow coming from outside and incrementing the domestic pollution.

Depending on the size of β_i, three types of pollution can be distinguished:

- $\beta_i \in \left[0, \frac{1}{2}\right[$: the pollution flow generated in one region is only partially domestically located but the major part of the pollution is deposited domestically. This case is characterized by "low-transboundary pollution". The special case where $\beta_i = 0$ corresponds to the "purely local pollution" situation. Purely local pollution (with $\beta_i = \beta_j = 0$) corresponds to the case studied in Van Marrewijk (2005), Lange and Quaas (2007) and Elbers and Withagen (2004).

- $\beta_i = \frac{1}{2}$: the pollution flow generated in region i is perfectly distributed between the two regions. In the special case where $\beta_i = \beta_j = \frac{1}{2}$, designated by "symmetric distribution of pollution", the pollution doesn't matter in terms of location. Workers' indirect utility functions are lowered by the same amount as in the original model without pollution. However, in terms of equilibrium configurations, this case corresponds to the one without pollution because the indirect differential utility function is not affected by this purely global pollution. For example, this kind of pollution corresponds to climate change issues.

- $\beta_i \in \left]\frac{1}{2}, 1\right]$: the pollution flow generated in one region is only partially domestically located and the major part of the pollution is deposited abroad. This case is called "higher-transboundary pollution". The unrealistic case where $\beta_i = 1$ can be called "purely transboundary pollution".

permits simplification in exposition.

Hereafter, two cases are considered regarding the relative values of β_i and β_j. In the first case, $\beta_A = \beta_B$ is assumed. The objective is to study equilibria configuration in a framework consistent with the one adopted by Krugman (1991): regions are symmetric also regarding environmental parameters. In the second case, we assume that $\beta_A \neq 0$ and $\beta_B = 0$. This case is more realistic regarding transboundary pollution issues observed empirically (with the exception of Climate Change issues corresponding to the case where $\beta_i = \beta_j = \frac{1}{2}$).

Finally, following Ottaviano (2001), the restriction $\alpha < \frac{\sigma}{2\sigma - 1}$ is imposed to ensure that the traditional sector is active in both countries.

Resolution of this model[2] leads to the following indirect utility differential function of the share of skilled workers in location A:

$$f(h) = g(h) + l(h) - v(h) \tag{5}$$

Equation (5) consists of three parts:

- $g(h) \equiv \ln \frac{h + \psi(1-h)}{\psi h + (1-h)}$; where $\psi \equiv \frac{\sigma\left(1+\rho^2\right) - \left(1-\rho^2\right)\alpha}{2\rho\sigma}$; measures the welfare value of the wage rate differential. This term can be positive or negative because it reflects two opposite effects: the "market crowding effect" and the "home market effect" (Krugman, 1991).
- $l(h) \equiv \frac{\alpha}{\sigma - 1} \ln \frac{h + \rho(1-h)}{\rho h + (1-h)}$; where $\rho \equiv \tau^{1-\sigma}$ represents the degree of trade freeness; measures the welfare values of price index differences.
- $v(h) \equiv \delta\left[(1 - 2\beta_A) h - (1 - 2\beta_B)(1-h)\right]$; where $\delta \equiv \varphi\xi^2$; measures the environmental damages differential. φ reflects the harmfulness of the emitted pollution. ξ reflects the pollution flow rejected by the production of the industrial goods. So, *ceteris paribus*, when one of this two parameters rises, δ also rises and this implies a negative impact on the indirect utility of the skilled workers.

It is assumed that migration is regulated by a simple Marshallian adjustment (see, among others, Forslid and Ottaviano (2003), p.234):

$$\overset{\circ}{h} \equiv \frac{dh}{dt} = \begin{cases} f(h) & \text{if } h \in \left]0,1\right[\\ \min\{0, f(1)\} & \text{if } h = 1 \\ \max\{0, f(0)\} & \text{if } h = 0 \end{cases} \tag{6}$$

In order to determine the various possible cases the three parts of $f(h)$ have to be studied through their first derivative. The following result is obtained:

$$g'(h) = \frac{1 - \psi^2}{\psi + h(1-h)(1-\psi)^2} \gtreqless 0 \Leftrightarrow \psi \lesseqgtr 1 \tag{7}$$

Equation (7) shows how the spatial distribution of skilled workers affects their relative wages in the two locations: if $\psi < 1$ (respectively $\psi > 1$)[3], the wages are larger (respectively smaller) in the location that is better endowed with skilled labor.

[2] This result is obvious on the basis of Ottaviono's results (Ottaviono, 2001) and regarding the functional form used for the damage function. Detailed calculations may be found in an Appendix A.

[3] Noting $\rho_w \equiv \frac{1 - \frac{\alpha}{\sigma}}{1 + \frac{\alpha}{\sigma}}$, it can be seen that $\psi = 1 \Leftrightarrow [\rho = \rho_w \vee \rho = 1]$. Moreover, $\lim_{\rho \longrightarrow 0} \psi = +\infty$ and $\psi|_{\rho = \sqrt{\rho_w}} = \frac{\sqrt{\sigma^2 - \alpha^2}}{\sigma}$. Since $\frac{d\psi}{d\rho} = \frac{(\sigma+\alpha)\left(\rho^2 - \rho_w\right)}{2\rho^2\sigma} \gtreqless 0 \Leftrightarrow \rho \gtreqless \sqrt{\rho_w}$: (i) if $\rho \in \left]0; \rho_w\right[$; $\psi > 1$; (ii) if $\rho \in \left]\rho_w; 1\right[$; $\psi \in \left]\frac{\sqrt{\sigma^2 - \alpha^2}}{\sigma}, 1\right[$.

$$l'(h) = \frac{\alpha\left(1-\rho^2\right)}{(\sigma-1)\left[\rho + h(1-h)(1-\rho)^2\right]} > 0 \tag{8}$$

(8) is explained by the fact that "[...] since imported varieties incur the trade cost, the price index is always lower where there are more skilled workers and therefore more varieties are produced locally." (Ottaviano, 2001, p.58).

The third part of $f(h), v(h)$, constitutes the new element that distinguishes the present model from that of Ottaviano (2001). Let us now briefly present the behavior of this term in the two cases considered in this study:

- Symmetric transboundary pollution: $\beta_A = \beta_B = \beta$

In this case, the different relations of interest are:

$$v(h) = -\delta(1-2\beta)(1-2h) \tag{9}$$

$$v'(h) = 2\delta(1-2\beta) \gtreqless 0 \Leftrightarrow \beta \lesseqgtr \frac{1}{2} \tag{10}$$

$$v(0) = -\delta(1-2\beta)\,;\; v\left(\frac{1}{2}\right) = 0;\; v(1) = \delta(1-2\beta) \tag{11}$$

So $v\left(\frac{1}{2}+z\right)$ (just as $g\left(\frac{1}{2}+z\right)$ and $l\left(\frac{1}{2}+z\right)$) is an odd function on the interval $z \in \left[-\frac{1}{2}, \frac{1}{2}\right]$. Moreover $v(h)$ is an increasing function of h if $\beta < \frac{1}{2}$ and a decreasing function if $\beta > \frac{1}{2}$. In the first case, pollution damage acts as a centrifugal force and as a centripetal force, in the second case. So (10) indicates that the environmental damage differential increases with h in the case of "low-transboundary pollution" and decreases in the case of "higher-transboundary pollution".

- Asymmetric transboundary pollution: $\beta_A \neq 0$; $\beta_B = 0$

In this case, the different relations of interest are:

$$v(h) = -\delta\left[1-2h(1-\beta_A)\right] \tag{12}$$

$$v'(h) = 2\delta(1-\beta_A) > 0 \tag{13}$$

$$v(0) = -\delta;\; v\left(\frac{1}{2}\right) = -\delta\beta_A;\; v(1) = \delta(1-2\beta_A) \tag{14}$$

When only region A emits transboundary pollution and region B emits purely local pollution, two cases are possible. The case where $\beta_A < \frac{1}{2}$ looks like the first one of the preceding situation. The interval of h for which this force involves skilled workers' migration from region B to region A is now however greater than $\left[0, \frac{1}{2}\right]$. If $\beta_A \geqslant \frac{1}{2}$, pollution damage always involves migration from region B to region A whatever the value of h.

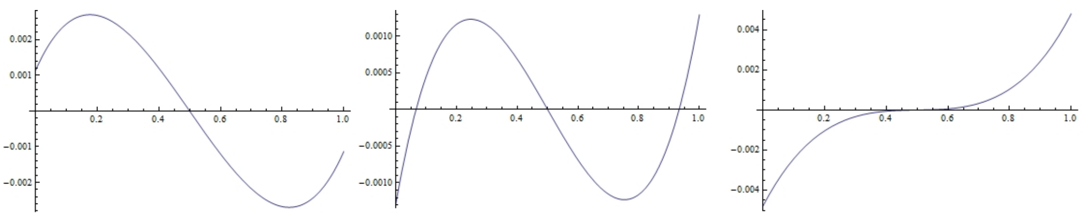
4 Typology of long-run equilibria[4]

First of all, let us examine what happens for global pollution, *i.e.* when $\beta_A = \beta_B = \frac{1}{2}$. This case corresponds to a benchmark case for which $v(h) = 0$ whatever the value of h. In terms of equilibrium configurations, it corresponds to the traditional case studied in the new geography economy, that of Ottaviano (2001). Let ρ_s be the degree of trade free-ness such as $\rho_s^{\frac{\alpha}{\sigma-1}} = \left(\psi|_{\rho=\rho_s}\right)^{-1}$ (*i.e.* the value corresponding to the "sustain point") and $\rho_b \equiv \frac{\sigma-1-\alpha}{\sigma-1+\alpha}\frac{\sigma-\alpha}{\sigma+\alpha}$ (*i.e.* the value corresponding to the "break point"). Depending on the value of ρ, this case can only lead to one of the three following equilibrium configurations[5].

If $\rho \in]0, \rho_s]$, *i.e.* in a situation of "high transport costs" there is a unique equilibrium ($h = \frac{1}{2}$) and this equilibrium is stable [see Figure 1 (a)[6]]. Thus, a diversified economy where both regions produce traditional and differentiated goods and they also have equal shares of skilled workers is obtained.

If $\rho \in]\rho_s, \rho_b[$, *i.e.* in a situation of "intermediate transport costs" there are three stable equilibria ($h = \left\{0, \frac{1}{2}, 1\right\}$), while a diversified production pattern with unequal shares of skilled workers represents an unstable equilibrium [see Figure 1 (b)]. In this case, depending on the initial share of skilled workers, both diversification and C-P patterns are possible.

Finally, if $\rho \in [\rho_b, 1]$, *i.e.* in a situation of "low transport costs" there are two stable equilibria ($h = \{0, 1\}$) and an unstable one ($h = \frac{1}{2}$) [see Figure 1 (c)]. This latter case leads to an agglomeration effect.



(a) $\rho \in]0, \rho_s]$ (b) $\rho \in]\rho_s, \rho_b[$ (c) $\rho \in [\rho_b, 1]$

Figure 1: Symmetric distribution of pollution

Now that the results of this benchmark case have been presented, we can compare them with the typology of long-run equilibria in the two cases of transboundary pollution, *i.e.* symmetric and asymmetric transboundary pollution.

Let us begin with the symmetric pollution case. First, two parameters are of interest concerning the configurations that can be raised in this case regarding the three intervals on the trade free-ness degree's values: β and δ. Especially, as said before regarding β's values, low and high-transboundary pollution can be distinguished.

In the first case (*i.e.* when $\beta < \frac{1}{2}$), pollution acts as a centrifugal force. Consequently, differential pollution reinforces spreading equilibrium configurations and weakens C-P configurations.

[4] All illustrations of the model cases were generated using the software Wolfram Mathematica 7.0.

[5] Equilibria in the symmetric distribution of the pollution case and long-run equilibria configurations in the presence of transboundary pollution (both in symmetric and asymmetric transboundary pollution situations) are thoroughly analytically derived and additional analyses are providing in the Appendices A to C.

[6] Figures 1 (a), (b) and (c) are respectively been obtained for $\rho = \{0.5, 0.504, 0.51\}$. Without any contrary mention, we used $\sigma = 3$ and $\alpha = 0.4$ for all figures in the paper.

In other words, in terms of localization, differential pollution favors the region where less skilled workers are located. However, specific results are obtained depending on the level of transport costs.

Obviously, in a situation of high transport costs, spreading equilibrium remains the only stable equilibrium regardless of the values of β and δ.

In a situation of intermediate transport costs, two cases are possible. If the negative impact of the transboundary pollution on the skilled workers' indirect utility (reflected by δ) is weak, the environmental damage differential is not sufficient to avoid the C-P equilibrium configuration. Therefore, the equilibrium configuration recalls the one in Figure 1 (b). However, if the centrifugal force generated by the environmental damage is strong enough to make core-periphery equilibria unstable, the spreading equilibrium is the only stable equilibrium and the equilibrium configuration becomes the one corresponding to Figure 1 (a). Similar observations can be made respectively for high and low values of β.

Finally, in a situation of low transport costs, three cases are possible. For weak values of δ (corresponding to a weak negative impact of the transboundary pollution on the skilled workers' indirect utility) or relatively high values of β, the environmental damage differential does not weaken the C-P equilibrium configuration enough to have significant impacts on the equilibrium configuration type and the equilibrium configuration recalls the one corresponding to Figure 1 (c). For intermediate values of δ and β, the environmental damage differential weakens the C-P equilibrium configuration and makes possible spreading equilibrium configurations but not sufficiently to make the C-P equilibrium configuration disappear and the equilibrium configuration becomes the one corresponding to Figure 1 (b). Finally, for high values of δ or relatively low values of β, the environmental damage differential weakens the C-P equilibrium configuration sufficiently to make only spreading equilibrium configurations possible and the equilibrium configuration becomes the one in Figure 1 (a).

Opposite effects occur in the case of high-transboundary pollution. Indeed when $\beta > \frac{1}{2}$ pollution acts as a centripetal force. In this case, differential pollution weakens the spreading equilibrium configuration and reinforces the C-P configuration. In other words, in terms of localization, differential pollution favors the region that is well-endowed with skilled labor.

First, it explains why, in a situation of low transport costs, C-P equilibria remain the only stable equilibria whatever the value of β and δ. In a situation of intermediate transport costs two cases are possible: for relatively low values of δ or β the equilibrium configuration recalls the one corresponding to Figure 1 (b), while for relatively high values of these parameters the equilibrium configuration becomes now the one corresponding to Figure 1 (c).

Actually, the most important difference between the two cases concerns the possibilities of partial agglomeration configurations in a situation of high transport costs. In this case, a new equilibrium configuration can arise in addition to the three corresponding to the benchmark case. For relatively low values of δ or β, the environmental damage differential does not weaken the spreading equilibrium configuration enough to have significant impact on the equilibrium configuration type. In this first case, the centripetal force generated by the environmental damage is not high enough to modify the equilibrium configuration which remains the one in Figure 1 (a). On the other hand, for relatively high values of δ or β, the environmental damage differential weakens the spreading equilibrium configuration sufficiently to make only the C-P equilibrium configuration possible and the equilibrium configuration becomes the one in Figure 1 (c).

Finally, in the case of intermediate values of δ or β in a situation of high transport costs, two cases are possible depending on the value of the degree of trade free-ness relative to a threshold value $\widetilde{\rho}$[7]. If the trade free-ness degree is below $\widetilde{\rho}$, the environmental damage differential

[7] $\widetilde{\rho} \in]0, \rho_b[$ is the unique value of transport cost such that $f(1)|_{\beta=\frac{1}{2};\rho=\widetilde{\rho}} = \frac{f'(\frac{1}{2})|_{\beta=\frac{1}{2};\rho=\widetilde{\rho}}}{2} < 0$. This result

weakens the spreading equilibrium configuration but does not reinforce the C-P equilibria enough to make them stable. It makes possible only partial agglomeration equilibria. This new case corresponds to the one in Figure 2. If the trade free-ness degree is above $\widetilde{\rho}$, the environmental damage differential weakens the spreading equilibrium configuration and makes possible the C-P equilibrium configuration but not sufficiently to make the spreading equilibrium configuration disappear. So the equilibrium configuration becomes the one in Figure 1 (b).

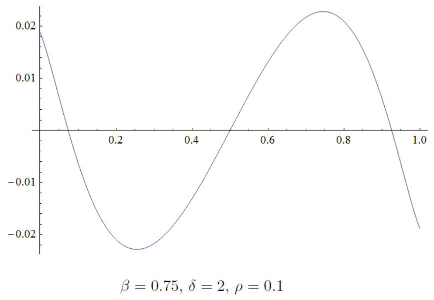


Figure 2: Asymmetric equilibrium configuration in a symmetric transboundary pollution case

Let us now analyze what happens in the asymmetric pollution case. Obviously, considering such a context (with $\beta_A \neq 0$ and $\beta_B = 0$) implies that symmetry is no longer an equilibrium and allows the possibility of obtaining more asymmetric equilibria because $v\left(\frac{1}{2}+z\right)$ is no longer an odd function on the interval $h \in \left[\frac{1}{2}, 1\right]$. An asymmetric transboundary pollution differential favors the migration of skilled workers towards A and leads to five new asymmetric equilibrium configurations represented in Figure 3.

The first configuration is similar to the one in Figure 1 (a) except that now the only stable equilibrium is an asymmetric one with most of the skilled workers in region A. This case is represented in Figure 3 (a). It occurs for asymmetric low-transboundary pollution ($\beta_A < \frac{1}{2}$) in the presence of high transport costs, in the presence of intermediate transport costs and in the presence of low transport costs for high values of δ and β_A. It also occurs for an asymmetric high-transboundary pollution ($\beta_A \geqslant \frac{1}{2}$) in the presence of high transport costs for low values of δ and β_A.

The second configuration is similar to the one in Figure 1 (b) except that (as in the latter case) the symmetric equilibrium is replaced by an asymmetric one with most of the skilled workers in region A. The core-periphery equilibria are still stable. This case is represented in Figure 3 (b). It occurs for asymmetric low-transboundary pollution in the presence of intermediate transport costs and low values of δ and β_A. It also occurs for asymmetric high-transboundary pollution in the presence of intermediate transport costs for low values of δ and β_A.

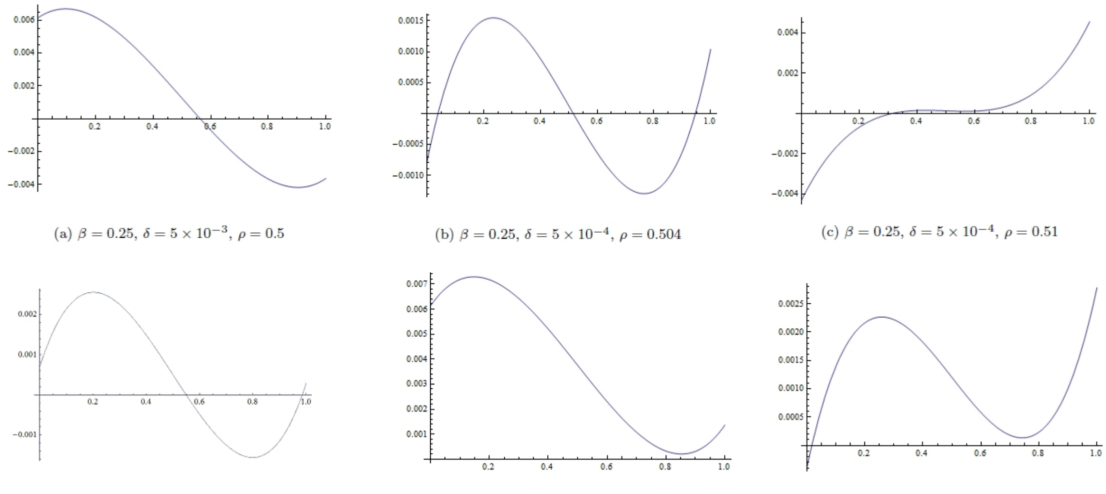
The third configuration is similar to the one in Figure 1 (c) except that the unstable symmetric equilibrium is replaced by an asymmetric one with most of the skilled workers in region A. The core-periphery equilibria are still stable but, in terms of occurrence, the interval of initial values of h leading to the Core in A – Periphery in B is wider than the one leading to the Core in B – Periphery in A. This case is represented in Figure 3 (c) and Figure 3 (f). It occurs for asymmetric low-transboundary pollution in the presence of low transport costs and low values of δ and β_A and for asymmetric high-transboundary pollution ($\beta_A > \frac{1}{2}$) and in the presence of intermediate transport costs for low values of δ and β_A. It also occurs for asymmetric high-transboundary

is proven in an Appendix B.4.

pollution in the presence of intermediate transport costs for intermediate values of δ and β_A and in the presence of low transport costs for low values of δ and β_A.

The fourth configuration is derived from the one in Figure 1 (b). In this configuration there are two stable equilibria. The first is asymmetric, with most of the skilled workers located in region A. The second is the Core in A – Periphery in B equilibrium which is still stable. The Core in B – Periphery in A equilibrium becomes unstable. In terms of occurrence, the interval of initial values of h leading to the asymmetric equilibrium is wider than the one leading to the Core in A – Periphery in B equilibrium. This case is represented in Figure 3 (d). It occurs for asymmetric low-transboundary pollution in the presence of intermediate transport costs and intermediate values of δ and β_A and in the presence of low transport costs for intermediate values of δ and β_A. It also occurs for asymmetric high-transboundary pollution in the presence of high transport costs for intermediate values of δ and β_A.

Finally, in the fifth configuration, derived from the one in Figure 1 (e), the only stable equilibrium is the Core in A – Periphery in B equilibrium. It occurs for asymmetric high-transboundary pollution whatever the types of cost for high values of δ and β_A.



(a) $\beta = 0.25$, $\delta = 5 \times 10^{-3}$, $\rho = 0.5$

(b) $\beta = 0.25$, $\delta = 5 \times 10^{-4}$, $\rho = 0.504$

(c) $\beta = 0.25$, $\delta = 5 \times 10^{-4}$, $\rho = 0.51$

(d) $\beta = 0.25$, $\delta = 2 \times 10^{-3}$, $\rho = 0.504$

(e) $\beta = 0.75$, $\delta = 5 \times 10^{-3}$, $\rho = 0.5$

(f) $\beta = 0.8$, $\delta = 1.5 \times 10^{-3}$, $\rho = 0.505$

Figure 3: New equilibrium configurations in case of asymmetric transboundary pollution

5 Conclusions

In this paper, we have studied the impact of transboundary pollution in terms of agglomeration regarding the values of transport costs which play a central role in NEG models. Two cases have been distinguished. In the first one, transboundary pollution is symmetric. Each region sends the same share of its pollution emission to the other region. In the second case, transboundary pollution is asymmetric. Only one region emits transboundary pollution, the other one emits purely local pollution and receives the share of pollution flow coming from outside and increasing domestic pollution. Moreover, all the cases where a stable asymmetric equilibrium can occur in the model were determined analytically.

For each type of transboundary pollution two cases were studied. In the case of "low-transboundary pollution", in which the largest share of pollution flow emitted in a region stays in that region, environmental damage is a "centrifugal force" rendering the agglomeration of activities less attractive. In the case of "high-transboundary pollution", in which the largest share of pollution flow emitted in one region damages the other region, environmental damage is a "centripetal force" rending the agglomeration of activities more attractive. This result is consistent with a similar result obtained by Van Marrewijk (2005).

In terms of equilibrium configurations, symmetric pollution does not involve new equilibrium configurations in any of the situations considered, except one. However, in most situations, the stability of equilibria is affected. It may be reinforced or weakened depending on the parameter values characterizing the impact of pollution.

In the case of asymmetric transboundary pollution, where one region emits transboundary pollution and the second emits purely local pollution, five new equilibrium configurations were obtained. A symmetric equilibrium no longer obtains. It has been replaced by an asymmetric equilibrium, with most of the skilled workers localized in the former region. Unilateral core-periphery equilibria, with the Core in the former region and the Periphery in the latter, may occur. These new equilibrium configurations in a NEG model are one of the main results of this paper.

However, we do not consider normative aspects of transboundary pollution, such as the consequences of environmental policies on the agglomeration of activities. Considerations of growth, through capital mobility, or pollution abatement could be interesting perspectives to improve the analysis conducted in this paper. These extensions form part of our research agenda.

6 Appendix A – Consumer Behavior and profit's maximization: short-run equilibria

As in Ottaviano (2001), utility maximization by residents and profit maximization by a typical firm located in $i = \{A, B\}$ give the following functions:

- Demand functions:

$$Y_i = (1-\alpha) I_i \text{ and } d_{ji}(m) = \frac{[p_{ji}(m)]^{-\sigma}}{q_i^{1-\sigma}} \alpha I_i; \; i,j = \{A, B\} \tag{15}$$

where $q_i = \left\{ \int_0^{n_i} [p_{ii}(m)]^{1-\sigma} dm + \int_0^{n_j} [p_{ji}(m)]^{1-\sigma} dm \right\}^{\frac{1}{\sigma-1}}$ is the local CES price index associated to (2) and $I_i = n_i R_i + L$ is the local income.

- First order conditions for profit's maximization give:

$$p_{ii}(m) = k \frac{\sigma}{\sigma - 1} = 1 \text{ and } p_{ij}(m) = \sigma \tag{16}$$

$$q_i = [n_i + \rho n_j]^{\frac{1}{\sigma-1}} = [Q_{ij}]^{\frac{1}{\sigma-1}} \tag{17}$$

where $\rho \equiv \tau^{1-\sigma} \in]0, 1]$ is the ratio of total demand by domestic residents for each foreign variety to their demand for each domestic variety. ρ can also be seen as reflecting the "freeness of trade"; with a situation varying from autarky ($\rho = 0$) to free trade ($\rho = 1$).

The free entry condition implies:

$$R_i = (1-k) x_i = \frac{x_i}{\sigma} \tag{18}$$

Using (15)-(18), we get:

$$x_i = \alpha \left\{ \frac{L + n_i \frac{x_i}{\sigma}}{Q_{ij}} + \frac{\rho \left[L + n_j \frac{x_j}{\sigma} \right]}{Q_{ji}} \right\} \tag{19}$$

Solving the system for $i = \{A, B\}$ yields:

$$\left. \frac{x_A}{x_B} \right|_h = \frac{h + \psi (1-h)}{\psi h + (1-h)} = \left. \frac{R_A}{R_B} \right|_h ; \ \psi \equiv \frac{\sigma \left(1+\rho^2\right) - \left(1-\rho^2\right) \alpha}{2\rho\sigma} \tag{20}$$

Given (1) and (4) the indirect utility of a skilled worker in location i is:

$$W_i = \ln \left[\frac{R_i}{q_i^{\alpha}} \right] - \varphi \xi^2 \left[(1-\beta_i) n_i + \beta_j n_j \right] \tag{21}$$

Finally, the indirect utility differential is:

$$f(h) \equiv W_A - W_B = \ln \left. \frac{R_A}{R_B} \right|_h - \alpha \left. \frac{q_A}{q_B} \right|_h - \varphi \xi^2 \left[(1-2\beta_A) h - (1-2\beta_B)(1-h) \right] \tag{22}$$

Appendix B – Equilibria in the symmetric distribution of pollution case

Appendix B.1. Determination of C-P and Spreading equilibria

In the case of a symmetric distribution of pollution:

$$\left. f(h) \right|_{\beta=\frac{1}{2}} \equiv \ln \frac{h + \psi(1-h)}{\psi h + (1-h)} + \frac{\alpha}{\sigma - 1} \ln \frac{h + \rho(1-h)}{\rho h + (1-h)} \tag{23}$$

$$\left. f'(h) \right|_{\beta=\frac{1}{2}} \equiv \frac{1-\psi^2}{\psi + h(1-h)(1-\psi)^2} + \frac{\alpha\left(1-\rho^2\right)}{(\sigma-1)\left[\rho + h(1-h)(1-\rho)^2\right]} \tag{24}$$

Note that:

$$\left. f(1) \right|_{\beta=\frac{1}{2}} \equiv -\ln \left[\psi \rho^{\frac{\alpha}{\sigma-1}} \right] \tag{25}$$

As shown by Ottaviano (2001) and Forslid and Ottaviano (2003), there is a unique value of ρ, noted ρ_s and called "sustain point", with $\rho_s < 1$, solution of the equation $\psi^{-1} = \rho^{\frac{\alpha}{\sigma-1}}$ and thus for which: $\left. f(1) \right|_{\beta=\frac{1}{2};\rho=\rho_s} = \left. f(1) \right|_{\beta=\frac{1}{2};\rho=\rho_s} = 0$.

Moreover: (i) $\forall \rho \in]0, \rho_s[$; $\left. f(1) \right|_{\beta=\frac{1}{2}} < 0$ (condition for which the C-P is unstable); (ii) $\forall \rho \in]\rho_s, 1]$; $\left. f(1) \right|_{\beta=\frac{1}{2}} > 0$ (condition for which the C-P is stable).

$$\left. f'\left(\frac{1}{2}\right) \right|_{\beta=\frac{1}{2}} \equiv 4 \left[\frac{1-\psi}{1+\psi} + \frac{\alpha(1-\rho)}{(\sigma-1)(1+\rho)} \right] = \frac{4(1-\rho)(\sigma-1+\alpha)(\rho-\rho_b)}{(\sigma-1)(1+\rho)(\rho+\rho_w)} \tag{26}$$

Where $\rho_b \equiv \frac{\sigma-1-\alpha}{\sigma-1+\alpha} \frac{\sigma-\alpha}{\sigma+\alpha} = \rho_z \rho_w$ is called "break point" and $\rho_z \equiv \frac{\sigma-1-\alpha}{\sigma-1+\alpha}$. Then: (i) $\forall \rho \in]0, \rho_b[$; $\left. f'\left(\frac{1}{2}\right) \right|_{\beta=\frac{1}{2}} < 0$ (condition for which the spreading equilibrium is stable); (ii) $\forall \rho \in]\rho_b, 1]$; $\left. f'\left(\frac{1}{2}\right) \right|_{\beta=\frac{1}{2}} > 0$ (condition for which the spreading equilibrium is unstable). Note that $\rho > \rho_b$ is always true if $\alpha > \sigma - 1$ (a « black hole » situation in the new economic geography literature), situation traditionally « ruled out ». So we suppose hereafter that $\sigma - 1 > \alpha$.

Moreover, it can be shown that $\rho_s < \rho_b$: (26) implies that $\left. \psi \right|_{\rho=\rho_b} = \frac{(\sigma-1)(1+\rho)+\alpha(1-\rho)}{(\sigma-1)(1+\rho)-\alpha(1-\rho)} > 1$. Then $\lim_{\alpha\to 0} \left. f(1) \right|_{\beta=\frac{1}{2};\rho=\rho_b} = \lim_{\alpha\to 0} \left\{ -\ln \left[\left. \psi \right|_{\rho=\rho_b} \rho^{\frac{\alpha}{\sigma-1}} \right] \right\} = 0$ and $\frac{d\left[\left. f(1) \right|_{\beta=\frac{1}{2}} \right]}{d\alpha} = \frac{1-\rho^2}{2\rho\sigma\psi} - \frac{\ln \rho}{\sigma-1} > 0$ imply $\left. f(1) \right|_{\beta=\frac{1}{2};\rho=\rho_b} > 0 \ \forall \alpha \in]0, 1]$. Then $\rho_b \in]\rho_s, 1]$.

Finally: $\rho_s < \rho_b < \rho_z < \rho_w < \sqrt{\rho_w}$.
The available situations, in absence of pollution, can be illustrated in table 1.

	$\rho < \rho_s$	$\rho > \rho_s$
$\rho < \rho_b$	Spreading Equilibrium stable	Spreading and C-P equilibria stable
$\rho > \rho_b$	Impossible	C-P Equilibrium stable

Table 1 - Possible Equilibrium configurations without pollution

Appendix B.2. C-P equilibria' behaviors

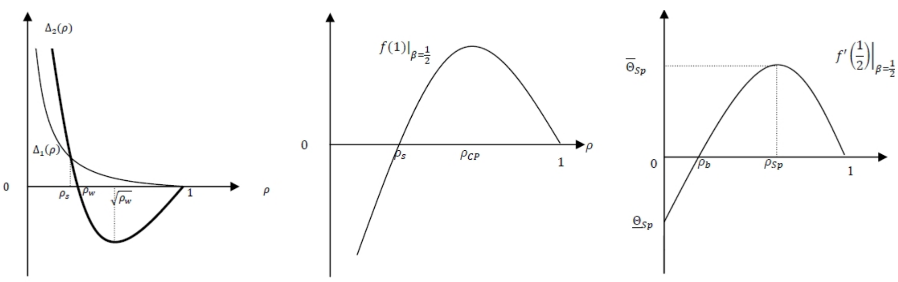
We know that:

$$f(1)|_{\beta=\frac{1}{2}} \equiv \Delta_1(\rho) - \Delta_2(\rho) \gtreqless 0 \Leftrightarrow \rho \gtreqless \rho_s \quad (27)$$

Where $\Delta_1(\rho) \equiv -\frac{\alpha}{\sigma-1}\ln\rho$ and $\Delta_2(\rho) \equiv \ln\psi$.

Note that $\Delta_1(\rho) > 0$; $\Delta_1'(\rho) = -\frac{\alpha}{(\sigma-1)\rho} < 0$; $\Delta_1''(\rho) = \frac{\alpha}{(\sigma-1)\rho^2} > 0$; $\forall\rho \in]0,1[$ and $\Delta_2(\rho) \gtreqless 0 \Leftrightarrow \psi \gtreqless 1$.

In addition: $\lim_{\rho\to 0}\Delta_1(\rho) = \lim_{\rho\to 0}\Delta_2(\rho) = +\infty$. Then, we can use L'Hospital's rule to assert that: $\lim_{\rho\to 0}\frac{\Delta_1(\rho)}{\Delta_2(\rho)} = \lim_{\rho\to 0}\frac{\Delta_1'(\rho)}{\Delta_2'(\rho)} = \frac{\alpha}{(\sigma-1)(\sigma+\alpha)} < 1$. Moreover: $\lim_{\rho\to 0} f(1)|_{\beta=\frac{1}{2}} \equiv -\infty$. $\Delta_1(\rho)$ and $\Delta_2(\rho)$ are represented in Figure 4(a).



(a) $\Delta_1(\rho)$ and $\Delta_2(\rho)$ (b) $f(1)|_{\beta=\frac{1}{2}}$ (c) $f'(\frac{1}{2})|_{\beta=\frac{1}{2}}$

Figure 4: C-P and spreading equilibriums' behaviours

Finally, note that $\frac{d\left[f(1)|_{\beta=\frac{1}{2}};\rho=\sqrt{\rho_w}\right]}{d\rho} = -\frac{\alpha}{(\sigma-1)\sqrt{\rho_w}} < 0 \Leftrightarrow \frac{(\sigma-1)(\sigma+\alpha)-\alpha}{(\sigma-1)(\sigma+\alpha)+\alpha} > \rho_b\rho_z$. According to the "no black hole" condition, this condition his verified because $\frac{(\sigma-1)(\sigma+\alpha)-\alpha}{(\sigma-1)(\sigma+\alpha)+\alpha} > \rho_z \Leftrightarrow \sigma - 1 > \alpha$.

Because the two functions are monotonically decreasing functions of ρ on $\left]0,\sqrt{\rho_w}\right[$ and according to (27) we can assert that: (i) for $\rho \in]0,\rho_s[$ $f(1)|_{\beta=\frac{1}{2}} < 0$ and takes all the values on $]-\infty,0[$; (ii) for $\rho \in]\rho_s,1]$ $f(1)|_{\beta=\frac{1}{2}} > 0$ and reach an unique maximum on this interval for $\rho_{CP} \equiv \sqrt{\rho_w\frac{(\sigma-1)(\sigma+\alpha)-\alpha}{(\sigma-1)(\sigma+\alpha)+\alpha}} = \sqrt{\frac{(\sigma-1)(\sigma+\alpha)-\alpha}{(\sigma-1)(\sigma+\alpha)+\alpha}\frac{\sigma-\alpha}{\sigma+\alpha}}$ [Cf., Figure 4(b)].

Appendix B.3. Spreading equilibrium' behaviors

Following (26), $f'\left(\frac{1}{2}\right)\Big|_{\beta=\frac{1}{2}} = \frac{4(\sigma-1+\alpha)\Lambda_1(\rho)}{(\sigma-1)}$, where $\Lambda_1(\rho) \equiv \frac{(1-\rho)(\rho-\rho_b)}{(1+\rho)(\rho+\rho_w)}$.

First, we see that $\Lambda_1(0) = -\frac{\rho_b}{\rho_w} = -\rho_z$ and $\Lambda_1(\rho_b) = \Lambda_1(1) = 0$.

Then, $\underline{\Theta}_{SP} \equiv \lim_{\rho\to 0} f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}} = -\frac{4(\sigma-1+\alpha)\rho_z}{(\sigma-1)}$ and $f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_s} = f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=1} = 0$.

Secondly, we have: $\Lambda_1'(\rho) = \frac{2\rho_b\rho_w+\rho_b+\rho_w-2\rho(\rho_w-\rho_b)-\rho^2(\rho_w+\rho_b+2)}{(1+\rho)^2(\rho+\rho_w)^2} = \frac{\Lambda_2(\rho)}{(1+\rho)^2(\rho+\rho_w)^2}$. The sign of $\Lambda_1'(\rho)$ depends on the sign of the quadratic function $\Lambda_2(\rho)$ and $\Lambda_2'(\rho) = -2\left[\rho_w - \rho_b + \rho(\rho_w+\rho_b+2)\right] < 0$. Then $f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}$ is a strictly concave function regarding ρ on $]0,1[$.

It can be easily seen that the quadratic equation $\Lambda_2(0) = 0$ has two real roots with opposite signs: $\overline{\rho}, \rho_{SP} \equiv \frac{\sqrt{(\rho_w-\rho_b)^2} - \sqrt{(\rho_w-\rho_b)^2+(\rho_w+\rho_b+2)(2\rho_w\rho_b+\rho_w+\rho_b)}}{(\rho_w+\rho_b+2)}$; $\overline{\rho} < 0$ and $\rho_{SP} > 0$. It is obvious that $\sqrt{\rho_w} < \rho_{SP}$.

Then: $\rho_{CP} < \sqrt{\rho_w} < \rho_{SP}$.

Finally, $\Lambda_2(\rho) = 0 \Leftrightarrow \rho = \{\overline{\rho}, \rho_{SP}\}$; $\Lambda_2(\rho) > 0 \Leftrightarrow \rho \in]\overline{\rho}, \rho_{SP}[$ and $\Lambda_2(\rho) < 0$ otherwise. Then, we can assert that under the same conditions $\Lambda_1(\rho)$ has a similar sign. Let $\overline{\Theta}_{SP} \equiv f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_{SP}}$ denote the maximum value of $f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}$. $f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}$ is represented in Figure 4(c).

Appendix B.4. Relative behavior of C-P and Spreading equilibria

Determining the different configurations regarding the impact of environmental damage differential requires to know the relative behavior of $f(1)$ and $\frac{f'\left(\frac{1}{2}\right)}{2}$ regarding the value of ρ. Firstly, it can be noted that: $\lim_{\rho\to 0} \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}}{2} = \frac{\underline{\Theta}_{SP}}{2} > \lim_{\rho\to 0} f(1)\big|_{\beta=\frac{1}{2}} = -\infty$; $f(1)\big|_{\beta=\frac{1}{2};\rho=\rho_b} > \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_b}}{2} = 0$; $f(1)\big|_{\beta=\frac{1}{2};\rho=\rho_s} = 0 > \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_s}}{2}$; $f(1)\big|_{\beta=\frac{1}{2};\rho=1} = \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=1}}{2} = 0$.

Because $f(1)\big|_{\beta=\frac{1}{2}}$ and $\frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}}{2}$ are monotonically increasing functions regarding ρ on $[0,\rho_b]$, it can be asserted that there exists a unique value $\widetilde{\rho} \in]0,\rho_b[$ such that: $\widetilde{\Theta} \equiv f(1)\big|_{\beta=\frac{1}{2};\rho=\widetilde{\rho}} = \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\widetilde{\rho}}}{2} < 0$. Then, $f(1)\big|_{\beta=\frac{1}{2}} < \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}}{2}$ if $\rho \in]0,\widetilde{\rho}[$ and $f(1)\big|_{\beta=\frac{1}{2}} > \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}}{2}$ if $\rho \in]\widetilde{\rho},\rho_b[$.

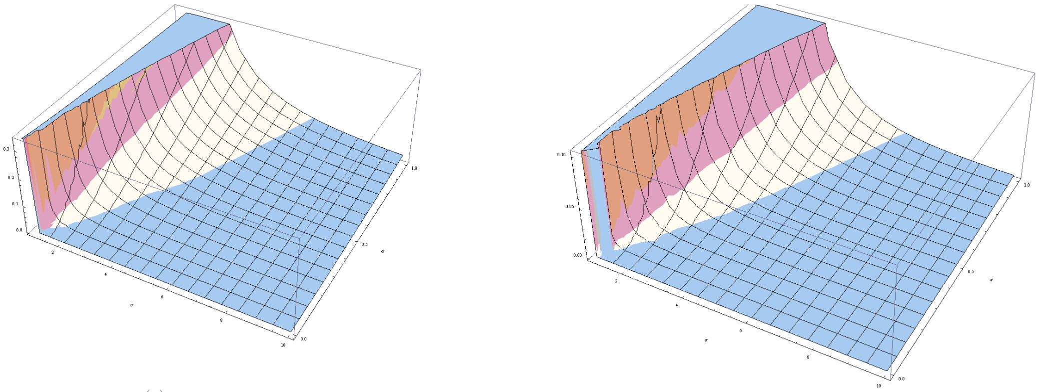
For $\rho \in]\rho_b, 1[$, $f(1)\big|_{\beta=\frac{1}{2}}$ and $\frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}}{2}$ are difficult to compare analytically. But, based on the evolution of these two functions on this interval, we can gain some insights using results from simulations. First, on $]\rho_b, \rho_{CP}[$, the two functions are monotonically increasing functions regarding ρ. Because $f(1)\big|_{\beta=\frac{1}{2};\rho=\rho_b} > \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_b}}{2} = 0$, if $f(1)\big|_{\beta=\frac{1}{2};\rho=\rho_{CP}} > \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_{CP}}}{2}$, it implies that $f(1)\big|_{\beta=\frac{1}{2}} > \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}}{2}$; $\forall\rho \in [\rho_b, \rho_{CP}]$. Drawing $f(1)\big|_{\beta=\frac{1}{2};\rho=\rho_{CP}} - \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_{CP}}}{2}$, it can be seen that it is always true [we use $\sigma \in [1;10]$ whatever $\alpha \in]0,1[$ for Figures 5(a) and (b)[8]]. Then, it can be infered that on $[\rho_b, \rho_{CP}]$; $f(1)\big|_{\beta=\frac{1}{2}} - \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}}{2} > 0$.

Secondly, since the two functions are monotonically decreasing on $]\rho_{SP}, 1]$ and since the value of these functions is null for $\rho = 1$, when $f(1)\big|_{\beta=\frac{1}{2};\rho=\rho_{SP}} - \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_{SP}}}{2} \gtreqless 0$ this inequality is also verified $\forall\rho \in]\rho_{SP}, 1[$.

Finally, $f(1)\big|_{\beta=\frac{1}{2}}$ and $\frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}}}{2}$ are, respectively, monotonically decreasing and increasing on $]\rho_{CP}, \rho_{SP}[$. Then, if $f(1)\big|_{\beta=\frac{1}{2};\rho=\rho_{SP}} - \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_{SP}}}{2} > 0$, the inequality is also verified $\forall\rho \in]\widetilde{\rho}, 1[$. If $f(1)\big|_{\beta=\frac{1}{2};\rho=\rho_{SP}} - \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\rho_{SP}}}{2} < 0$, $\exists!\widehat{\rho} \in]\rho_{CP}, \rho_{SP}[$ such that $f(1)\big|_{\beta=\frac{1}{2};\rho=\widehat{\rho}} = \frac{f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2};\rho=\widehat{\rho}}}{2}$.

[8] Figures 5(a) and (b) were generated using the software Matlab R2010.a.

Then $f(1)|_{\beta=\frac{1}{2}} > \frac{f'\left(\frac{1}{2}\right)|_{\beta=\frac{1}{2}}}{2}$; $\forall \rho \in]\rho_{CP}, \widehat{\rho}[$ and $f(1)|_{\beta=\frac{1}{2}} < \frac{f'\left(\frac{1}{2}\right)|_{\beta=\frac{1}{2}}}{2}$ $\forall \rho \in]\widehat{\rho}, 1[$. Distinction between this two cases is not analytically easy. However, we can again gain some insights using results from simulations. We draw $f(1)|_{\beta=\frac{1}{2};\rho=\rho_{SP}} - \frac{f'\left(\frac{1}{2}\right)|_{\beta=\frac{1}{2};\rho=\rho_{SP}}}{2}$. Results obtained show that $f(1)|_{\beta=\frac{1}{2};\rho=\rho_{SP}} - \frac{f'\left(\frac{1}{2}\right)|_{\beta=\frac{1}{2};\rho=\rho_{SP}}}{2} > 0$.



(a) $\rho = \rho_{CP}$

(b) $\rho = \rho_{SP}$

Figure 5: $f(1)|_{\beta=\frac{1}{2}} - \frac{f'\left(\frac{1}{2}\right)|_{\beta=\frac{1}{2}}}{2}$; $\rho = \{\rho_{CP}, \rho_{SP}\}$

Appendix C – Long-run equilibria configurations in presence of transboundary pollution

Appendix C.1. Symmetric transboundary pollution

According to the results obtained in Appendix B, for the three possible cases regarding the interval values of ρ (high, intermediate and low transport costs), we need to study the possible impacts of a symmetric transboundary pollution regarding values of β and δ. Because $f\left(\frac{1}{2}+z\right)\Big|_{\beta=\frac{1}{2}}$ and $v\left(\frac{1}{2}+z\right)$ are odd functions on $z \in \left[-\frac{1}{2}, \frac{1}{2}\right]$ in case of symmetric transboundary pollution, the analysis can be restrained on the interval $h \in \left[\frac{1}{2}, 1\right]$.

Low-transboundary pollution: $\beta < \frac{1}{2}$

- High transport costs, $\rho \in]0, \rho_s]$: in this case $f(h)|_{\beta=\frac{1}{2}} < 0$ and $v(h) > 0$; $\forall h \in \left[\frac{1}{2}, 1\right]$. Then $f(h) = f(h)|_{\beta=\frac{1}{2}} - v(h) < 0$; $\forall h \in \left[\frac{1}{2}, 1\right]$.

- Intermediate transport costs, $\rho \in]\rho_s, \rho_b[$; in this case, for a given $\rho_2 \in]\rho_s, \rho_b[$:

$$f(1)|_{\beta=\frac{1}{2}} \equiv \phi_2 > 0;\ f'\left(\tfrac{1}{2}\right)\Big|_{\beta=\frac{1}{2}} \equiv -2\theta_2 < 0;\ f'\left(\tfrac{1}{2}\right) = -2\left[\theta_2 + \delta(1-2\beta)\right] < 0.$$

If $\phi_2 > \delta(1-2\beta) \Rightarrow f(1) = \phi_2 - \delta(1-2\beta) > 0$, the equilibrium configuration remains the one of Figure 1(b). If $\phi_2 < \delta(1-2\beta) \Rightarrow f(1) < 0$[9], the equilibrium configuration becomes the

[9] Rigorously speaking, we should also envisage the case where $\phi_2 = \delta(1-2\beta)$. But this case does

one of Figure 1(c). When $\beta < \frac{1}{2}$; $\frac{dv(1)}{d\delta} = (1-2\beta) > 0$; $\frac{dv'\left(\frac{1}{2}\right)}{d\delta} = 2(1-2\beta) > 0$; $\frac{dv(1)}{d\beta} = -2\delta < 0$ and $\frac{dv'\left(\frac{1}{2}\right)}{d\beta} = -4\delta < 0$. Therefore, for a given ρ_2 when δ increases or β decreases the equilibrium configuration successively corresponds to Figure 1(b) and (a).

- Low transport costs, $\rho \in [\rho_b, 1]$:

Let's consider a given $\rho_3 \in [\rho_b, 1]$. We compare $f(1)|_{\beta=\frac{1}{2}} \equiv \phi_3 > 0$ and $v(1) = \delta(1-2\beta)$, on one hand, and $f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}} \equiv 2\theta_3 > 0$ and $v'\left(\frac{1}{2}\right) = 2\delta(1-2\beta)$, on the other hand. Comparisons have to be made considering that (as demonstrated in Appendix B.4.) $\phi_3 > \theta_3$. If $\phi_3 > \theta_3 > \delta(1-2\beta) \Rightarrow f(1) = \phi_3 - \delta(1-2\beta) > 0$ and $f'\left(\frac{1}{2}\right) = 2[\theta_3 - 2\delta(1-2\beta)] > 0$, the equilibrium configuration remains the one of Figure 1(c). If $\phi_3 > \delta(1-2\beta) > \theta_3 \Rightarrow f(1) > 0$ and $f'\left(\frac{1}{2}\right) < 0$, the equilibrium configuration becomes the one of Figure 1(b). If $\delta(1-2\beta) > \phi_3 > \theta_3 \Rightarrow f(1) < 0$ and $f'\left(\frac{1}{2}\right) < 0$, the equilibrium configuration becomes the one of Figure 1(a). For similar reasons to those given above, when δ increases or β decreases, the equilibrium configuration successively corresponds to Figure 1(c), 1(b) and 1(a).

High-transboundary pollution: $\beta > \frac{1}{2}$

- High transport costs, $\rho \in]0, \rho_s]$:

For a given $\rho_1 \in]0, \rho_s]$, we compare $f(1)|_{\beta=\frac{1}{2}} \equiv -\phi_1 < 0$ and $v(1) = \delta(1-2\beta) < 0$, on one hand, and $f'\left(\frac{1}{2}\right)\big|_{\beta=\frac{1}{2}} \equiv -2\theta_1 < 0$ and $v'\left(\frac{1}{2}\right) = 2\delta(1-2\beta) < 0$, on the other hand. Now four cases are possible regarding the values of δ, β and ρ_1.

If $\phi_1 > \theta_1 > \delta(2\beta-1)$ or $\theta_1 > \phi_1 > \delta(1-2\beta) \Rightarrow f(1) = -\phi_1 - \delta(1-2\beta) < 0$ and $f'\left(\frac{1}{2}\right) = -2[-\theta_3 + 2\delta(1-2\beta)] < 0$, the equilibrium configuration remains the one of Figure 1(a). If $\phi_1 > \delta(2\beta-1) > \theta_1$ (which can only happens if $\rho \in]0, \widetilde{\rho}[$) $\Longrightarrow f(1) > 0$ and $f'\left(\frac{1}{2}\right) < 0$, the equilibrium configuration becomes the one of Figure 2. If $\theta_1 > (2\beta-1) > \phi_1$ (which can only happens if $\rho \in]\widetilde{\rho}, \rho_s]$) $\Longrightarrow f(1) < 0$ and $f'\left(\frac{1}{2}\right) > 0$, the equilibrium configuration becomes the one of Figure 1(b). If $(2\beta-1) > \phi_1 > \theta_1$ or $\delta(1-2\beta) > \theta_1 > \phi_1 \Rightarrow f(1) > 0$ and $f'\left(\frac{1}{2}\right) > 0$, the equilibrium configuration becomes the one of Figure 1(c). Because $\frac{dv(1)}{d\delta} = (1-2\beta) < 0$; $\frac{dv'\left(\frac{1}{2}\right)}{d\delta} = 2(1-2\beta) < 0$; $\frac{dv(1)}{d\beta} = -2\delta < 0$ and $\frac{dv'\left(\frac{1}{2}\right)}{d\beta} = -4\delta < 0$, for a given ρ_1 when δ or β increase the equilibrium configuration successively corresponds to Figure 1(a), Figure 2 or Figure 1(b) and Figure 1(c)

- Intermediate transport costs, $\rho \in]\rho_s, \rho_b[$. In this case, for a given $\rho_2 \in]\rho_s, \rho_b[$: $\phi_2 > 0$; $-2\theta_2 < 0$; $f(1) = \phi_2 - \delta(1-2\beta) > 0$. If $\phi_2 > \delta(2\beta-1) \Rightarrow f'\left(\frac{1}{2}\right) = -2[\theta_2 + \delta(1-2\beta)] < 0$, the equilibrium configuration remains the one of Figure 1(b). If $\phi_2 < \delta(2\beta-1) \Rightarrow f'\left(\frac{1}{2}\right) > 0$, equilibrium configuration becomes the one of Figure 1(c). For similar reasons to those given above, for a given ρ_2, when δ or β increase, the equilibrium configuration successively correspond to Figure 1(b) and 1(c).

- Low transport costs, $\rho \in [\rho_b, 1]$: in this case $\phi_3 > 0$ and $v(h) < 0$; $\forall h \in \left[\frac{1}{2}, 1\right]$. Then $f(h) > 0$; $\forall h \in \left[\frac{1}{2}, 1\right]$.

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not change substantially the equilibrium configuration. It is similar to the one of Figure 1(a). So, for purpose of presentation, we don't specifically present this case. We adopt, hereafter, similar presentation choices when this type of equalities do not lead to changes in terms of equilibrium configurations.

Appendix C.2. Asymmetric transboundary pollution

In a context of asymmetric transboundary pollution, $v\left(\frac{1}{2}+z\right)$ is no longer an odd function. Three impacts of the environmental damages differential will now be considered regarding the traditional case where $\beta=\frac{1}{2}$: (i) the impact on $f(0)$; this impact can be determined comparing $f(0)|_{\beta=\frac{1}{2}}$ and $v(0)=-\delta$; (ii) the impact on $f(1)$; this impact can be determined comparing $f(1)|_{\beta=\frac{1}{2}}$ and $v(1)=\delta(1-2\beta_A)$; (iii) the impact in terms of interior equilibria (values of $h\in]0,1[$ such that $f(h)=0$). Due to asymmetrical transboundary pollution, $h=\frac{1}{2}$ is no longer an equilibrium. So we have to determine the number of possible intersections between $f(h)|_{\beta=\frac{1}{2}}$ and $v(h)$ regarding their relative shapes and the stability properties at the different interiors equilibria.

Low-transboundary pollution: $\beta_A<\frac{1}{2}$

In an asymmetric low-transboundary pollution situation:

$v(0)=-\delta<0$; $v\left(\frac{1}{2}\right)=-\delta\beta_A<0$, $v(1)=\delta(1-2\beta_A)>0$, $v'(h)=2\delta(1-\beta_A)>0$.

There exists a unique value $\overline{h}\equiv\frac{1}{2(1-\beta_A)}\in\left]\frac{1}{2},1\right[$ such that $v\left(\overline{h}\right)=-\delta\left[1-2\overline{h}(1-2\beta_A)\right]=0$

- High transport costs, $\rho\in]0,\rho_s]$: in this case, $f(0)=\phi_1+\delta>0$, $f(1)=-\phi_1-\delta(1-2\beta_A)<0$ and $f\left(\overline{h}\right)<0$. Based on the continuity and the shapes of $f(h)|_{\beta=\frac{1}{2}}$ and $v(h)$, we can assert that there exists a unique value $h_1\in\left]\frac{1}{2},\overline{h}\right[$ such that $f(h_1)=0$. This case corresponds to the one of Figure 3(a).

- Intermediate transport costs, $\rho\in]\rho_s,\rho_b[$: three cases are possible regarding relative values of ϕ_2 and δ, on the one hand, and relative values of ϕ_2 and $\delta(1-2\beta_A)$, on the other hand. If $\phi_2>\delta>\delta(1-2\beta_A)$, then $f(0)<0$ and $f(1)>0$. Based on the continuity and the shapes of $f(h)|_{\beta=\frac{1}{2}}$ and $v(h)$, and because $f\left(\frac{1}{2}+z\right)\Big|_{\beta=\frac{1}{2}}$ is an odd function on $z\in\left[-\frac{1}{2},\frac{1}{2}\right]$, there exist three values h_{2i}; $i=\{1,2,3\}$; such that $f(h_{2i})=0$: $h_{21}\in\left]0,\frac{1}{2}\right[$; $h_{22}\in\left]\frac{1}{2},\overline{h}\right[$ and $h_{23}\in\left]\overline{h},1\right[$. In this case, the only stable equilibrium is h_{22}. This case corresponds to the one of Figure 3(b). If $\delta>\phi_2>\delta(1-2\beta_A)$, then $f(0)>0$ and $f(1)=\phi_1-\delta(1-2\beta_A)>0$. For the same reasons as before, there exist now two values h_{2i}; $i=\{1,2\}$; such that $f(h_{2i})=0$: $h_{21}\in\left]\frac{1}{2},\overline{h}\right[$ and $h_{22}\in\left]\overline{h},1\right[$. In this case, there are two stable equilibria: h_{21} and $h=0$. It corresponds to Figure 3(d). If $\delta>\delta(1-2\beta_A)>\phi_2$, then $f(0)>0$ and $f(1)<0$. For the same reasons as before, there exists a unique value h_2 such that $f(h_2)=0$: it corresponds to Figure 3(a). Because $\frac{dv(0)}{d\beta_A}=0$ and $\frac{dv'(h)}{d\beta_A}=-2\beta_A$ for a given $\rho_1\in]0,\rho_s]$, when β_A increases, situations successively correspond to the first, second and third cases. It is also obvious that the same results arise when δ increases.

- Low transport costs, $\rho\in[\rho_b,1]$: in this case three cases are possible regarding relative values of ϕ_3 and δ, on the one hand, and relative values of ϕ_3 and $\delta(1-2\beta_A)$, on the other hand. If $\phi_3>\delta>\delta(1-2\beta_A)$ then $f(0)<0$ and $f(1)>0$. For the same reasons as before, there exists a unique value of h such that $f(h)=0$. It corresponds to Figure 3(c). If $\delta>\phi_3>\delta(1-2\beta_A)$ then $f(0)>0$ and $f(1)>0$. For the same reasons as before, there exist two values of of h such that $f(h)=0$. It corresponds to Figure 3(d). If $\delta>\delta(1-2\beta_A)>\phi_3$ then $f(0)>0$ and $f(1)<0$. For the same reasons as before, there exists a unique value of of h such that $f(h)=0$. It corresponds to Figure 3(a). As before, when β_A or δ increase, situations successively correspond to the first, second and third cases.

High-transboundary pollution: $\beta\geqslant\frac{1}{2}$

In an asymmetric high-transboundary pollution situation, $v(0)=-\delta<0$; $v(1)=\delta(1-2\beta_A)<0$ and $v'(h)=2\delta(1-\beta_A)<0$. Then, $v(h)<0$; $\forall h\in[0,1]$.

- High transport costs, $\rho \in]0, \rho_s]$. If $\phi_1 > \delta > \delta(2\beta_A - 1)$, then $f(0) > 0$ and $f(1) < 0$. For the same reasons as before, there exists a unique value of h such that $f(h) = 0$. It corresponds to Figure 3(a). If $\delta > \phi_1 > \delta(2\beta_A - 1)$, then $f(0) > 0$ and $f(1) > 0$. Two cases are possible depending on the relative values of $v(h^*)$ and $f(h^*)|_{\beta=\frac{1}{2}}$ where $h^* \equiv \frac{1+\sqrt{(1+4\gamma)}}{2} \in \left]\frac{1}{2}, 1\right[$ is the unique value on this interval such that $f'(h^*)|_{\beta=\frac{1}{2}} = 0$ and where $\gamma \equiv \frac{\frac{(\sigma-1)[1+\psi(\rho_1)]\rho_1}{1-\rho_1} - \frac{\alpha(1+\rho_1)\psi(\rho_1)}{\psi(\rho_1)-1}}{(\sigma-1+\alpha)[\psi(\rho_1)(\rho_z-\rho_1)+(1-\rho_z\rho_1)]}$ and $\psi(\rho_1) = \frac{\sigma(1+\rho_1^2)-(1-\rho_1^2)\alpha}{2\rho_1\sigma}$. If $v(h^*) > f(h^*)|_{\beta=\frac{1}{2}}$[10], there exist two values h_{1i}; $i = \{1, 2\}$; such that $f(h_{1i}) = 0$ with $(h_{11}, h_{12}) \in \left(\left]\frac{1}{2}, 1\right[\right)^2$ and $h_{11} > h_{12}$. Then there are two stable equilibria: h_{11} and $h = 1$. It corresponds to Figure 3(d). If $v(h^*) < f(h^*)|_{\beta=\frac{1}{2}}$, then $f(h) > 0; \forall h \in [0, 1]$. It corresponds to Figure 3(e). As before, when β_A or δ increase, situations successively correspond to the first, second and third cases.

- Intermediate transport costs, $\rho \in]\rho_s, \rho_b[$. Three cases are possible regarding relative values of ϕ_2 and δ. If $\phi_2 > \delta$ then $f(0) < 0$. Two cases are possible depending on the relative values of $v(h^*)$ and $f(h^*)|_{\beta=\frac{1}{2}}$: (i) if $v(h^*) > f(h^*)|_{\beta=\frac{1}{2}}$[11], there exist three values h_{2i}; $i = \{1, 2, 3\}$; such that $f(h_{2i}) = 0$: $h_{21} \in \left]0, \frac{1}{2}\right[$ and $(h_{22}, h_{23}) \in \left(\left]\frac{1}{2}, 1\right[\right)^2$ whit $h_{22} > h_{23}$; then there are three stable equilibria: h_{22} and $h = \{0, 1\}$ and it corresponds to Figure 3(b); (ii) if $v(h^*) < f(h^*)|_{\beta=\frac{1}{2}}$, there exist a unique value h_2 such that $f(h_2) = 0$ with $h_2 \in \left]0, \frac{1}{2}\right[$; it corresponds to Figure 3(f). If $\phi_2 < \delta$, then $f(h) > 0$; $\forall h \in [0, 1]$; it corresponds to Figure 3(e). When β_A and δ increase, situations successively correspond to the first and second cases.

- Low transport costs, $\rho \in [\rho_b, 1]$: two cases are possible regarding relative values of ϕ_3 and δ. If $\phi_3 > \delta$ then $f(0) < 0$. For the same reasons as before, there exist a unique value of h such that $f(h) = 0$. It corresponds to the Figure 3(c). If $\delta < \phi_3$ then $f(0) > 0$ and $f(h) > 0$; $\forall h \in [0, 1]$. It corresponds to Figure 3(e). As before, when β_A or δ increase, situations successively correspond to the first, and second cases.

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[10] If $v(h^*) = f(h^*)|_{\beta=\frac{1}{2}}$ there exists a unique value $h \in \left]\frac{1}{2}, 1\right[$ such that $f(h)$ is tangent to the abscissa axe. Stable equilibriums are the same as the ones of Figure 3(d) but the unstable asymmetric equilibrium disappears.

[11] If $v(h^*) = f(h^*)|_{\beta=\frac{1}{2}}$ then $f(h^*)$ is tangent to the abscissa axe. Stable equilibriums are the same as the ones of Figure 3(b) but the two unstable asymmetric equilibriums disappear.

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