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A Simple Model of Agglomeration Economies with Environmental Externalities

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A Simple Model of Agglomeration Economies with Environmental Externalities

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Summary

This paper develops a simple though comprehensive economic theory of the relationship between space and environment. It generalizes earlier modeling efforts to address agglomeration and environmental externalities in a location-trade framework of the new economic geography (NEG) literature. The model combines a number of features: industrial location, energy intensity, production- and trade-related environmental externalities, and migration. The major innovation is an endogenous "market-density effect". This influences environmental pollution as well as the distribution of the population and economic activities across regions. In addition, we account for an explicit spatial dimension through heterogeneous patterns of land use and development. The model extends previous NEG studies by deriving analytical conditions that enable continuous and asymmetric distributions of population and economic activity across space when the environmental and agglomeration externalities are accounted for, and this for the whole range of trade costs. This makes it suitable for addressing the spatial economic and trade dimensions of environmental problems and paves the way for policy-relevant applications.

Keywords: Energy use, Land use, Market density, Market form, New economic geography, Pollution, Regional and urban Economics, Spatial configurations, Trade.

JEL Classification: F12, F18, Q56, R12.

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I. Introduction

Despite the lack of well-coordinated national and international strategies to effectively cope with global environmental concerns, a rapidly increasing number of cities and metropolitan areas are taking action on environmental degradation worldwide (OECD, 2010). Although few studies exist that empirically recognize the potential contribution of cities and spatial organization to environmental conservation (Glaeser and Khan, 2010; Grazi *et al.*, 2008) a well-structured economic theoretical framework to study the environmental and welfare impacts of the distribution of economic activities and households across space is still lacking. Yet this is necessary to support the design of effective policy with theoretically well-founded insights on environmentally sustainable as well as economically efficient use of space (European Commission, 2011).

This paper presents such a theoretical framework, developed in the form of a general equilibrium model motivated by the new economic geography (NEG) (Krugman, 1991). It integrates three important economic mechanisms that influence both welfare and environmental performance of the economy: namely, positive agglomeration externalities; negative environmental externalities; interregional trade. Positive externalities from agglomeration are due to shorter travel distances, technological spillovers and knowledge sharing, improved local labor markets, and easier interactions between industries. Recently, Zeng and Zhao (2009) have argued that such agglomeration externalities can affect the emission of pollution by manufacturing firms through their impact on the efficiency of energy inputs in production. Wagner and Timmins (2009) provide empirical evidence for this and draw attention to the fact that positive externalities affect the spatial concentration of certain pollution-intense industrial activities. To address the direct and indirect energy-use effects of spatial economic organization and associated environmental externalities, the model proposed here will include a regional energy sector.

With respect to the standard NEG framework, our model presents a number of innovative features. The major innovation is that it considers an additional endogenous centrifugal force associated with agglomeration spillover effects at the industry level. This allows to simultaneously model standard increasing returns to scale at the firm level and external economies at the industry level. We refer to it as the 'market-density effect' and argue that it is key to economic welfare and environmental quality, since it determines the extent to which spatial concentration of economic activities affects the scale of pollution externalities. Moreover, in addition to the usual inter-regional scale of investigation, our model explicitly accounts for the intra-regional spatial dimension (affecting total output of economic activity) through analysis of spatial configurations of the economy with urbanized and undeveloped areas. The model describes transitions between these configurations. Because of these features, it allows for an evaluation of the impact of trade policies and intra-regional spatial planning on the economy and environment.

Following Krugman's seminal work (1991), a considerable literature on the NEG emerged addressing the mechanisms through which economies develop in space. Studies combine location choice, transport cost, trade barriers, and imperfect market competition in a mathematically tractable framework. A variety of issues have been tackled, including trade taxes, regulation of transport, and lobbying associated with factor mobility.[1] But few NEG studies have covered environmental issues, and none has explicitly addressed the connection between spatial and economic structures when environmental externalities are accounted for. Brakman *et al.* (1996), Hosoe and Naito (2005), and Calmette and Pechoux (2007) examine congestion and pollution as a dampening agglomerative force, but did not offer analytical solutions. Pfluger (2001) builds an analytically solvable model with monopolistic competition *à la* Krugman (1980, 1991) but neglects the implication of both pollution and labor mobility on the spatial distribution of economic activities across regions. Rauscher (2003) also develops a NEG model with pollution and obtains analytical solutions but at the cost of assuming quasi-linear preferences, which gives a partial-equilibrium flavor to his approach. Eppink and Withagen (2009) study biodiversity conservation in the context of regional economic specialization and development with an analytically solvable NEG model, but address a purely local environmental externality (namely biodiversity loss). Zeng and Zhao (2009) investigate the pollution haven hypothesis by embedding pollution into the standard "footloose capital" model, a variant of Krugman's (1991) 'Core-Periphery' model that describes the migration of capital when labor is immobile (Martin and Rogers, 1995; Baldwin *et al.*, 2003). However, the analytical tractability of this model is realized by ignoring the negative impacts of pollution on household utility.

In this paper we use an analytically solvable variant of Krugman's (1991) model, the "footloose entrepreneur (FE)" model developed by Forslid and Ottaviano (2003). This model has become quite popular because it yields closed-form solutions. A disadvantage is that it may give rise to spatial equilibria that are more extreme than what one tends to find in reality (what is called the 'catastrophic agglomeration' result) (Ottaviano, 2003). By formalizing a smooth transition from economic agglomeration to dispersion and continuously variable degrees of heterogeneity of land development within each region, we overcome this limitation of the framework.

[1] For an overview of the NEG literature, see Fujita *et al.* (1999), Fujita and Thisse (2002), and Ottaviano and Thisse (2004).

A few other contributions have employed the Forslid and Ottaviano framework to incorporate pollution and analyze how this relates to agglomeration. Van Marrewijk (2005) and Grazi *et al.* (2007) focus on quasi-static and static short-run equilibria, respectively. Lange and Quaas (2007) provide a dynamic analysis of pollution and agglomeration, but do not consider the positive effects of agglomeration on pollution through technological and knowledge-sharing spillovers. The outcome is a partial description of reality, resulting in environmental externalities dominating the final equilibrium outcome in certain cases. In contrast, our model accounts for two effects of agglomeration spillovers on environmental pollution which work in opposite directions, as explained below.

Agglomeration spillover effects have received attention in the economic literature on trade theory and urban economics since Marshall and Chamberlin. Nevertheless, their formal representation has turned out to be difficult and controversial (Ciccone, 2002). Moreover, to the best of our knowledge, to date no study has achieved a simultaneous modeling of increasing returns to scale at the firm level *à la* Dixit and Stiglitz (1977), as is standard in NEG models, and agglomeration externalities at the industry level *à la* Scitovsky (1954).[2] Our work tries to accomplish this, and for this purpose adds to the increasing returns to scale operating at the firm level an endogenous agglomeration effect variable defined at the industry level. In particular, the intensity of the agglomeration spillover is defined as a function of: *i*) a regional 'market form' effect, which is associated with the structure (organization) of the economic system and captured by the capacity of various types of infrastructure (such as for electricity, transport and telecommunications); and *ii*) a regional 'market density' effect, which depends on the density of economic activity, captured by the number of firms active in the industry. Including these factors allows us to investigate within a NEG framework the effects of density externalities, electricity and transport infrastructure and knowledge sharing on the energy intensity of production, which in turn influences the production structure within the region.[3]

Our approach includes a number of minor innovative features. First, the spatial dimension of the economy is strengthened through the introduction of a regional energy sector, which contributes to intra-industry agglomeration externalities. Second, agglomeration affects environmental pollution through two mechanisms,

[2] Chapter 7 in Baldwin *et al.* (2003) may be considered as an alternative attempt to model increasing returns at the firm level in combination with external economies at the industry scale. However, this attempt builds on a completely different endogenous-growth setting *à la* Grossman and Helpman (1991) which deviates from the NEG literature taken as a starting point here.

[3] Behrens *et al.* (2006) and Martin and Rogers (1995) also address (dis)economies created by job density and infrastructure endowment. However, they focus on the effect of spatial spillovers on trade of final goods and not on the spatial structure of production.

which, ex ante make the net effect non-obvious. One effect is that agglomeration increases the scale of production activity by lowering the cost of production and hence leads to more energy use and associated emissions. The other is that agglomeration reduces the energy requirements for production through technological (R&D and learning) spillovers. This in turn leads to an improvement in the energy efficiency of technologies used by economic production activities and associated lower emissions.

The remainder of this paper is organized as follows. Section II develops a general location-trade modeling framework of the new economic geography (NEG) literature with agglomeration economies and environmental pollution externalities. Section III derives the conditions under which qualitatively different equilibria arise if agglomeration and pollution externalities are accounted for. Section IV finally concludes.

II. The Spatial Economy

II.1. The short-run model

The model describes a global economy consisting of two regions (labeled $j \in \{1,2\}$) and three production sectors. One produces an intermediate good energy ξ for the industrial sectors by employing a fixed amount of immobile unskilled work force L. A second sector is manufacturing, denoted by the symbol M, which produces a continuum of i varieties of a horizontally-differentiated final good through mobile skilled labor H and energy ξ as input factors. A third sector is an aggregated sector, denoted by the symbol Q, which produces a homogeneous traditional final good using only immobile unskilled labor L. M is characterized by increasing returns and monopolistic competition *à la* Dixit and Stiglitz (1977). Because of consumer preferences for variety and increasing returns to scale, each firm specializes in producing a distinct variety of the manufactured good. Hence, the total number of active firms in the two-region economy, $N = n_1 + n_2$ equals the number of varieties available in the market. The traditional and energy service sectors produce under Walrasian conditions (constant returns to scale and perfect competition). The traditional good is chosen as the *numéraire* (i.e. its price is set at unity).

For the purpose of assessing environmental and welfare effects of using space and energy, we explicitly model a pollutive energy sector as a variable input of production. The energy sector is subject to an endogenous technological spillover that alters the energy intensity of production and which is related to the degree of spatial concentration of economic activities within the region. In line with a Krugman-like modeling setting, international trade of the composite manufacturing good occurs at a certain cost, whereas trade costs are zero for both inter- and intra-regional shipment of the traditional good. $L = L_1 + L_2$ and $H = H_1 + H_2$ denote the total of unskilled and skilled laborers, respectively. In the initial spatial setting, skilled workers are mobile and may be unevenly distributed across the two regions; the share of skilled workers living in region 1 is denoted by h, with $h = H_1/H$. Unskilled workers, on the other hand, are assumed to be immobile and evenly spread across regions, so that $L_j = L/2$. Each unskilled worker supplies one unit of labor.

II.1.1. Households

Workers maximize utility by consuming the two goods and suffer from negative effects on utility because of external environmental effects associated with economic activity. Aggregate utility is a Cobb-Douglas function of consumption of the traditional commodity Q and consumption of the aggregate manufactured good M. The latter is modeled as a CES function of consumption levels $c_{jj}(i)$ and $c_{kj}(i)$ of a particular variety i of the manufactured good that is sold in region j and produced in regions j and k.[4]

The negative effect of the environmental externality on utility is captured by a multiplicative term $\Theta\left(E_j^L\right)$, which is a function of the local flows of pollution, E_j^L. Many earlier studies employed an additive functional form to achieve analytical results (e.g. Rauscher, 2003); Lange and Quaas, 2007); Elbers and Withagen, 2004). This comes down to assuming constant marginal disutility associated with the environmental externality. Unlike these studies we treat the environmental externality as part of a multiplicative utility function, which ensures a more realistic relationship between pollution and utility, while still allowing for analytical solutions of the model. This modeling choice is moreover in line with a theoretical study of appropriate functional forms to describe environmental externalities (Ebert and Welsch, 2004).

(1)
$$U_j = M_j^{\delta} Q_j^{1-\delta} \Theta\left(E_j^L\right), \quad j = (1,2); \Theta\left(E_j^L\right) \leq 1, \text{ with:}$$
$$M_j = \left[\int_{i=0}^{n_j} c_{jj}(i)^{(\varepsilon-1)/\varepsilon} di + \int_{i=0}^{n_k} c_{kj}(i)^{(\varepsilon-1)/\varepsilon} di\right]^{\frac{\varepsilon}{\varepsilon-1}}, \quad j,k = \left(1,2\right);\ j \neq k;\ i \in N.$$

[4] For ease of notation, we drop the index i for varieties in the remainder of the paper.

Here, $0 < \delta < 1$ is the share of income Υ_j spent on manufactures; $\varepsilon > 1$ is the elasticity of substitution between varieties; and $\Theta\left(E_j^L\right)$ is the damage function associated with local flows of pollution E_j^L which alters individuals' utility in *j*.

Domestic consumption of traded goods c_{kj} results from standard utility maximization:

(2) $$c_{kj} = \frac{(p_{kj})^{-\varepsilon}}{I_j^{1-\varepsilon}} \Upsilon_j, \quad j,k = \left(1,2\right); j \neq k.$$

Here p_{kj} is the delivered price of a good produced in *k* and consumed in *j*, and $I_j = [n_j p_j^{1-\varepsilon} + n_k p_{kj}^{1-\varepsilon}]^{1/(1-\varepsilon)}$ is Dixit-Stiglitz's (1977) price index of the manufactured good in *j*.

II.1.2. Firms

Manufacturing firms produce using both skilled labor H and energy ξ as inputs. Skilled workers are hired at a wage rate w_j, while energy is paid a price p^ξ independent of the region *j* considered. The cost structure of a typical *j*-firm which produces a quantity x_j of the manufactured good entails fixed costs in human capital, αw_j, and variable costs in terms of energy requirements per unit of output, $p^\xi \xi_j$:

(3) $$\chi_j = \alpha w_j + p^\xi \xi_j x_j.$$

Here ξ_j represents the energy intensity of regional production in manufacturing.

Trade occurs between the two regions. To avoid modeling a separate interregional transportation sector, we use the 'iceberg' form of transport costs associated with the interregional trade of manufactured goods (Samuelson, 1952). This means that if a variety of the manufactured good produced in location *j* is sold in the same region at price p_{jj} then it will be charged a price p_{jk} in consumption location *k* that satisfies $p_{jk} = p_{jj} T_{jk}$. Here $T_{jk} > 1$ is the iceberg unitary trade cost of the manufactured good, which represents the number of goods sent per unit received. We assume that interregional trade costs are the same in each direction, $T = T_{jk} = T_{kj}$.

Next we formalize an agglomeration spillover and consider the impact of spatial clustering of economic activities on the production cost of the regional manufacturing sector by identifying two region-specific drivers of the energy intensity of regional production ξ_j:

$$\xi_j = \beta_j \bar{\psi}\left(n_j\right), \quad \beta_j > 0; \; 0 \le \bar{\psi}\left(n_j\right) \le 1. \tag{4}$$

The first driver is the parameter β_j, which captures the impact of regional spatial form, related to, and captured by, the regional infrastructure endowment, on the energy intensity of regional production in manufacturing. The second driver, $\bar{\psi}\left(n_j\right)$, is an *endogenous* spillover effect at the industry level and represents the equivalent impact of market density, which is function of the number of firms that are active in the regional market when its spatial extension is determined. In the remainder of the paper, we refer to β_j as the "market-form effect" and to as the "market-density effect".

We can think of parameter β_j this as capturing (being inversely related to) the degree of 'urbanization' of a given spatial economy, or the spatial concentration of regional (electricity, transport and telecommunications) infrastructure networks, which alters the demand for energy in the production process. Since infrastructure is characterized by slow dynamics or inertia, β_j is treated as an exogenous parameter. Two possible spatial forms (or structures) for each region are considered: namely, a spatially-developed organization of manufacturing activities, with a high intensity of infrastructure development (urbanized space), and a less intense use of space by these activities on (undeveloped) land. We consider a two-region system, which then gives rise to three possible spatial configurations of $\bar{\psi}\left(n_j\right)$ the global economy (urban + undeveloped; urban + urban; and undeveloped + undeveloped).[5]

The multiplicative term $\bar{\psi}\left(n_j\right)$ captures the impact of the market density on technological spillovers.[6] In line with empirical evidence on the effect of density of the economic activity on the structure of production (Ciccone and Hall, 1996; Ciccone, 2002; Keller, 2002; Duranton and Puga, 2004; Combes *et al.*, 2008), we posit

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[5] Actually, with the two possible regional structures described, $2^2 = 4$ spatial configurations for the two-region economy are possible. However, two of these are spatial mirror images of each other.

[6] The 'market-density' external effect that we model acts so as to reduce the average cost of production at the *industry* level, thus overriding the firm scale. As such it can be identified with external economies in the sense of Scitovsky (1954).

$\bar{\psi}(0)=1$ to indicate no positive effect of agglomeration on production costs in the absence of firms; and $\bar{\psi}'(n_j)<0$ to mean that the higher the number of firms, the lower the production costs.

Given eq. (3), profit-maximization leads to mark-up pricing for the manufactured good:

(5) $$p_j = \frac{\varepsilon}{\varepsilon - 1} p^{\xi} \xi_j.$$

The traditional good and the energy commodity are produced using unskilled labor as a linear input.[7] Production in the traditional sector is assumed to have a one-to-one relationship with unskilled labor and final product, whereas in energy service supply the labor requirement per unit of output is captured by parameter γ. We posit that the wage of unskilled workers equals unity.[8] Marginal cost pricing in the energy sector then implies:

(6) $$p^{\xi} = \gamma.$$

Production of the traditional good is:

(7) $$Q_j = L / 2 - \gamma \xi_j n_j x_j,$$

where the second term on the right-hand side of (7) represents the effect of unskilled workers being employed in the energy sector [see eq.(3)].

II.1.3. Market equilibrium

For a given regional distribution of the skilled labor factor H_j, the short-run model is determined by a set of four equations (for details, see Grazi *et al.*, 2007).

(8) $$\Upsilon_j = w_j H_j + L / 2.$$

[7] The assumption of linearity in the traditional/agricultural constant returns sector is very standard (Krugman, 1991). We extend it to the transport service sector in order to keep the analysis simple.

[8] This is a consequence of assuming free trade for the *numéraire* traditional good Q, which in turn comes down to its price being equal to 1 across regions: $p_j^Q = p_k^Q = p^Q = 1$, with $j,k = \{1,2\}$. Marginal cost pricing implies the interregional equalization of the wages of unskilled labor input L used in the traditional sector: $p^Q = w^L = 1$.

Here, Υ_j is the income generated in each region by w_j, the wage rate of skilled workers, H_j, and the *numéraire* wage of L_j unskilled workers.

$$(9) \qquad n_j = H_j \alpha^{-1},$$

where a fixed input requirement α indicates that the total number of firms operating in region *j*, n_j, is proportional to locally available skilled laborers.

As a consequence of the profit maximization behavior in a monopolistically competitive market, in both regions firms will enter and exit the manufacturing sector until the point at which profits are zero. Therefore, by substituting (5) into the profit function $\pi_j = p_j x_j - \chi_j$ and setting $\pi_j = 0$, the wage rate w_j at the equilibrium is:

$$(10) \qquad w_j = \frac{\gamma \xi_j x_j}{\alpha(\varepsilon - 1)}.$$

The market-clearing size of a typical firm in equilibrium is $x_j = c_{jj} + Tc_{jk}$. Substituting (2), (5) and (6) in (10) gives equilibrium solutions for x_j and I_j:

$$(11) \qquad \begin{aligned} x_j &= \delta \left[\frac{\gamma \xi_j \varepsilon}{\varepsilon - 1}\right]^{-\varepsilon} \left(\frac{\Upsilon_j}{I_j^{1-\varepsilon}} + \frac{\phi \Upsilon_k}{I_k^{1-\varepsilon}}\right), \text{ with} \\ I_j &= \frac{\varepsilon}{\varepsilon - 1} \gamma \left(n_j \xi_j^{1-\varepsilon} + \phi n_k \xi_k^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}, \quad 0 \le \phi \le 1. \end{aligned}$$

Here $\phi = T^{1-\varepsilon}$ is the standard NEG parameter measuring the freeness of interregional trade, with $\phi = 0$ representing maximal barriers to interregional trade (or autarky), and $\phi = 1$ free trade across regions.[9]

Given eq. (9) and recalling that the share of the population in region 1 equals $h = H_1 / H$, the *market density* effect $\bar{\psi}\left(n_j\right)$ in (4) can be re-written as a function of *h*: $\psi\left(h\right)$ in region 1 and $\psi\left(1-h\right)$ in region 2. Moreover, substituting equations (8), (9) and (11) into (10), using the definition of the regional share of population *h* and

[9] In the NEG approach, transport costs allow one to study the extent to which space affects economic decisions by individual agents (consumers and producers), and how these decisions in turn drive the spatial distribution of economic activities.

introducing $\Lambda\left(\phi\right) = 1 - \frac{\delta}{\varepsilon} + \left(1 + \frac{\delta}{\varepsilon}\right)\phi^2$ the model can be analytically solved in the regional wage levels w_1 and w_2:

$$(12)\quad \begin{aligned} w_1 = {} & \frac{\delta / \varepsilon}{1 - \delta / \varepsilon} \frac{L}{2H} \beta_1^{1-\varepsilon} \psi(h)^{1-\varepsilon} \cdot \\ & \cdot \frac{2\phi\beta_1^{1-\varepsilon}\psi(h)^{1-\varepsilon} h + \Lambda\left(\phi\right)\beta_2^{1-\varepsilon}\psi(1-h)^{1-\varepsilon}\left(1-h\right)}{\phi\left[\beta_1^{2(1-\varepsilon)}\psi(h)^{2(1-\varepsilon)}h^2 + \beta_2^{2(1-\varepsilon)}\psi(1-h)^{2(1-\varepsilon)}(1-h)^2\right] + \Lambda\left(\phi\right)\beta_1^{1-\varepsilon}\beta_2^{1-\varepsilon}\psi(h)^{1-\varepsilon}\psi(1-h)^{1-\varepsilon}h(1-h)}; \end{aligned}$$

$$(12bis)\quad \begin{aligned} w_2 = {} & \frac{\delta / \varepsilon}{1 - \delta / \varepsilon} \frac{L}{2H} \beta_2^{1-\varepsilon} \psi(1-h)^{1-\varepsilon} \cdot \\ & \cdot \frac{2\phi\beta_2^{1-\varepsilon}\psi(1-h)^{1-\varepsilon}\left(1-h\right) + \Lambda\left(\phi\right)\beta_1^{1-\varepsilon}\psi(h)^{1-\varepsilon} h}{\phi\left[\beta_1^{2(1-\varepsilon)}\psi(h)^{2(1-\varepsilon)}h^2 + \beta_2^{2(1-\varepsilon)}\psi(1-h)^{2(1-\varepsilon)}(1-h)^2\right] + \Lambda\phi\beta_1^{1-\varepsilon}\beta_2^{1-\varepsilon}\psi(h)^{1-\varepsilon}\psi(1-h)^{1-\varepsilon}h(1-h)}. \end{aligned}$$

II.1.4. Pollution externalities

The small literature that exists on NEG with agglomeration and environmental externalities considers the local effect of pollution (flow), meaning the (immediate) negative impact on the utility of individuals living in the respective region (Rauscher, 2003; Van Marrewijk, 2005; Lange and Quaas, 2007). Like these studies, we initially assume that the environmental externality (pollution) is local and only generated by manufacturing. Yet, unlike these studies, we reject the standard assumption of proportionality of pollution to the output of the *j*-manufacturing sector, x_j, and instead consider pollution as a by-product of energy use in production, ξ_j. We do assume proportionality between total energy use, $\xi_j n_j x_j$, and emissions of local pollutants in region *j* as follows:

$$(13)\qquad E_j^L = a^L \xi_j n_j x_j.$$

One can think of E_j^L as sulphur oxides, nitrogen oxides, carbon monoxide and particulate matters emitted from the combustion of fossil fuels and affecting air quality. For the sake of simplicity, we assume that the intensity of externalities generated by the energy input a^L in (13) remains constant, which boils down to neglecting technical progress of changes in the energy mix of regional production.[10]

[10] An alternative way to model local pollution would be to relate this to the marginal input factor unskilled labor, as in Copeland and Taylor (2004). Our formulation, although simple, has the advantage of specifying explicitly the impact mechanism via the energy requirements for production which allows specifying the impact of agglomeration on emission intensity.

The pollution term in utility, $\Theta\left(E_j^L\right)$ [see eq. (1)] captures the effect of pollution externalities on utility. We posit $\Theta\left(0\right)=1$ to indicate no negative effect of pollution on utility in the absence of any flow of pollution; and $\Theta'\left(E_j^L\right)<0$ to mean that the higher the pollution level, the stronger is its negative effect on utility.[11]

II.2. The long-run model and the dynamics of migration

Next, we study the long-term impact of different spatial configurations on production allocation when agglomeration- and local pollution-related effects matter. As in the "footloose entrepreneur" framework (Forslid and Ottaviano, 2003) the model dynamics is driven by international migration of individuals belonging to the skilled population. The resulting spatial equilibria are defined over the share h of skilled workers living in region 1, where $h = H_1/H$. Then the study of dynamic behavior of the core model variables is carried out for different values of trade barrier, ϕ. Consequently, all the variables in the dynamics analysis (wage, price index, pollution externality, etc.), can be expressed as functions of variables h and ϕ [$w_j(h,\phi)$, $I_j(h,\phi)$, $E_j^L(h,\phi)$, etc.].

The dynamics of migration and resulting spatial equilibria follow from individuals comparing wages, the price index and environmental externalities at different locations, as captured by the indirect utility differential between region 1 and 2: $\Omega(h,\phi)=V_1(h,\phi)-V_2(h,\phi)$. Here the indirect utility V_j associated with (1) is specified as:

$$V_j(h,\phi)=\Gamma\frac{w_j(h,\phi)}{I_j(h,\phi)^{\delta}}\Theta(h,\phi),\qquad j=\left(1,2\right), \tag{14}$$

where $\Gamma=\delta^{\delta}(1-\delta)^{1-\delta}$ is a constant that depends on the share of income devoted to manufacturing good purchases, δ.

Substituting (14) in the indirect utility differential $\Omega(h,\phi)$ gives the following derived relationship, which represents the incentive to move from region 2 to region 1:

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[11] Note that given equation (9) and dependence of local emissions, E_j^L, on the size of the regional market, n_j, in (13), the environmental-impact function, $\Theta\left(E_j^L,n_j\right)$, can be re-written as a function of the regional share of skilled workers, $h=H_1/H:\Theta\left(h\right)$. This relation will be adopted in the remainder of the long-run analysis.

$$(15) \qquad \Omega(h,\phi) = \Gamma\left[\frac{w_1(h,\phi)}{I_1(h,\phi)^{\delta}}\Theta(h,\phi) - \frac{w_2(h,\phi)}{I_2(h,\phi)^{\delta}}\Theta(1-h,\phi)\right].$$

Given $h \in [0;1]$, the equation describing the dynamics of factor mobility can be expressed as follows:[12]

$$(16) \qquad \frac{dh}{dt} = \begin{cases} \Omega(h,\phi), & \text{if } 0 < h < 1 \\ \max(0,\Omega(h,\phi)), & \text{if } h = 0 \\ \min(0,\Omega(h,\phi)), & \text{if } h = 1 \end{cases}.$$

Clearly, a long-run spatial equilibrium is defined by condition:

$$(17) \qquad \frac{dh}{dt} = 0.$$

Substituting (15) and (16) into (17) gives the implicit relationship between the distribution of population h and the trade barrier ϕ in the long run. Such an equilibrium is stable only if $\frac{\partial\Omega}{\partial h}(h,\phi) < 0$. For a given spatial configuration, a certain pattern of population distribution associated with a trade barrier level ϕ defines a stable long-run equilibrium if one of the three following conditions holds:

$$(18) \qquad a)\begin{cases} 0 < h < 1 \\ \Omega(h,\phi) = 0, \frac{\partial\Omega}{\partial h}(h,\phi) < 0 \end{cases}; \quad b)\begin{cases} h = 1 \\ \Omega(h,\phi) \geq 0 \end{cases}; \quad c)\begin{cases} h = 0 \\ \Omega(h,\phi) \leq 0 \end{cases}.$$

III. Equilibrium with Agglomeration and Pollution

This section examines the stability of long-run spatial equilibria if one accounts for agglomeration spillover effects at the industry level. The latter include the exogenous *market form* and endogenous *market density* effects, as well as the pollution flow effect. In so doing we complement standard analysis of the effect of agglomeration on the spatial equilibrium carried out with "footloose entrepreneur" models *à la* Forslid and Ottaviano (2003). As is standard in NEG literature since Krugman (1991), the analysis of equilibrium distinguishes between two centripetal forces driving

[12] Note that dynamics are implicit-in-time in this type of modeling framework (Krugman, 1991). This allows us to omit the index for time dependence from the variables of the long-run model.

agglomeration of economic activities (namely, 'market size' and 'cost-of-living') and one centrifugal force fostering their dispersion (namely, 'market crowding').[13]

To this set-up we add two further agglomeration/dispersion effects. One concerns the effect of environmental externalities on agglomeration patterns, a centrifugal force, which captures that agglomeration of production increases local pollution, which negatively affects utility of household. An environmental externality was also introduced in van Marrewijk (2005) and Lange and Quaas (2007), although with some differences.[14] The other effect represents the major innovation of our model with respect to these previous studies and consists of an additional centripetal force associated with agglomeration spillover effects at the industry level, formalized through an endogenous "*market density*" effect [see eq. (4)]. This effect captures that footloose entrepreneurs, when they migrate to a region, increase the number of active firms hence facilitating technological spillovers, resulting in lower production costs.[15] Table 1 summarizes and compares our contribution to the analysis of the determinants of spatial equilibria in the context of a NEG framework.

Table 1: Agglomeration effects in different NEG models

Model	*Centripetal effects*	*Centrifugal effects*
Forslid and Ottaviano (2003)	Market size Cost-of-living	Market crowding
Lange and Quaas (2007)	Market size Cost-of-living	Market crowding Environmental externality
This study	Market size Cost-of-living Market density	Market crowding Environmental externality

By substituting (12), (12*bis*), and (11) into (15), the latter can be rewritten as:

[13] See Baldwin *et al.* (2003) for an exhaustive discussion of centrifugal and centripetal forces driving the equilibrium in the standard NEG framework.

[14] While van Marrewijk (2005) looks at the effect of pollution on utility of agents in a quasi-dynamic framework, Lange and Quaas (2007) adopt a dynamic model with pollution externalities, but use an additive functional form for pollution in individuals' utility, which assumes constant marginal disutility due to the environmental externality. Here we develop a dynamic model with pollution more realistically affecting utility through a multiplicative factor, which implies increasing marginal disutility due to cumulative pollution effects over 'time'.

[15] In addition to the endogenous *market density* effect, we also introduce a *market form* effect associated with regional spatial organization. For the sake of simplicity, this is exogenous, reflected by a fixed value of β.

$$(19)\ \ \Omega(h,\phi)=\frac{\frac{\Gamma'}{\beta_1^{\delta}}\omega(h,\phi)}{\phi\left[h^2\psi(h)^{2(1-\varepsilon)}+(1-h)^2\left(\psi(1-h)\frac{\beta_2}{\beta_1}\right)^{2(1-\varepsilon)}\right]+\Lambda\left(\phi\right)h(1-h)\left(\frac{\beta_2}{\beta_1}\psi(h)\psi(1-h)\right)^{1-\varepsilon}}.$$

Here $\Gamma'=\Gamma\frac{\delta/\varepsilon}{1-\delta/\varepsilon}\frac{L}{2H}\left[\frac{(\varepsilon-1)\alpha^{\frac{1}{1-\varepsilon}}}{\gamma\varepsilon}\right]^{\delta}$ is a positive parameter and ω is a function that depends on variables ϕ and h in the following way:

$$(20)\ \ \omega(h,\phi)=\frac{\psi(h)^{1-\varepsilon}\left\{2h\phi\psi(h)^{1-\varepsilon}+\left(\frac{\beta_2}{\beta_1}\right)^{1-\varepsilon}\left[1-\frac{\delta}{\varepsilon}+\phi^2\left(1+\frac{\delta}{\varepsilon}\right)\right](1-h)\psi(1-h)^{1-\varepsilon}\right\}}{\left[h\psi(h)^{1-\varepsilon}+\left(\frac{\beta_2}{\beta_1}\right)^{1-\varepsilon}\phi(1-h)\psi(1-h)^{1-\varepsilon}\right]^{\frac{\delta}{1-\varepsilon}}}\Theta(h,\phi)+$$
$$-\frac{\left(\frac{\beta_2}{\beta_1}\right)^{1-\varepsilon}\psi(1-h)^{1-\varepsilon}\left\{2\phi\left(\frac{\beta_2}{\beta_1}\right)^{1-\varepsilon}(1-h)\psi(1-h)^{1-\varepsilon}+\left[1-\frac{\delta}{\varepsilon}+\phi^2\left(1+\frac{\delta}{\varepsilon}\right)\right]h\psi(h)^{1-\varepsilon}\right\}}{\left[h\phi\psi(h)^{1-\varepsilon}+\left(\frac{\beta_2}{\beta_1}\right)^{1-\varepsilon}(1-h)\psi(1-h)^{1-\varepsilon}\right]^{\frac{\delta}{1-\varepsilon}}}\Theta(1-h,\phi).$$

Note that the formulation in (19) of the indirect utility differential driving migration decisions by economic agents generalizes the result obtained by Forslid and Ottaviano (2003) in three ways: *i*) it allows for a variable positive agglomeration spillover associated with the density of market [i.e. $\psi(h)\leq 1$]; *ii*) it includes an environmental externality that negatively affects the utility of individuals [i.e. $\Theta(h,\phi)\leq 1$]; and *iii*) it enables to represent *ex-ante* differences in the regional form of the market (i.e. β_1 and β_2 may take different values). On the other hand, setting $\psi(h)=1$, $\Theta(h,\phi)=1$ and $\beta_1=\beta_2$ in equation (19) produces the same results as Forslid and Ottaviano (2003).

To be maximally consistent with the original framework by Forslid and Ottaviano (2003), we start by deriving equilibrium conditions for *ex-ante* identical regions $\left(\beta_1=\beta_2\right)$ (sub-section *III.1*), before turning to consider different *market forms* $\left(\beta_1\neq\beta_2\right)$ (sub-section *III.2*). In both cases, we follow the standard methodology of NEG analysis by investigating successively the stability conditions of the core-periphery ($h=1$) and symmetric spreading ($h=0.5$) patterns before deriving additional general equilibrium conditions. Finally, the results are interpreted and discussed in the light of the interplay between agglomeration and environmental drivers (sub-section *III.3*).

The key innovation that moves this section beyond the previous NEG literature is that it analytically derives the general stability conditions for the partial agglomeration equilibria ($0.5 < h < 1$).[16]

III.1. Equilibrium of symmetric spatial configurations

Here we study the long-run equilibria associated with (18) in symmetric spatial configurations of the two-region economy (i.e. $\beta_j = \beta_k = \beta$). We limit the analysis to the case $0.5 \le h \le 1$, since the findings are symmetrical around $h = 0.5$.

III.1.1. Core-Periphery pattern in symmetric configurations

The possible stable core-periphery equilibrium outcomes ($h = 1$) are summarized by the following proposition:

PROPOSITION 1: Given $\Theta(1)$, $\psi(1)$, and $\sigma_{\text{CP}}^{\min} = \frac{\varepsilon - 1}{\varepsilon}\left(\frac{\varepsilon - \delta}{\varepsilon - 1 + \delta}\right)^{\frac{1}{2}\left(\frac{\delta}{\varepsilon-1}+1\right)}\left(\frac{\varepsilon - 1 - \delta}{\varepsilon + \delta}\right)^{\frac{1}{2}\left(\frac{\delta}{\varepsilon-1}-1\right)}$,

three cases must be distinguished according to the position of $\Theta(1)\psi(1)^{1-\varepsilon}$ with respect to $\sigma_{\text{CP}}^{\min}$ and 1:

CP–*i*: If $\Theta(1)\psi(1)^{1-\varepsilon} \le \sigma_{\text{CP}}^{\min}$, the full agglomeration is never an equilibrium, whatever the trade freeness;

CP–*ii*: If $\sigma_{\text{CP}}^{\min} < \Theta(1)\psi(1)^{1-\varepsilon} < 1$, the full agglomeration is a stable equilibrium for intermediate trade freeness $\phi \in \left[\underline{\phi}_S;\overline{\phi}_S\right]$, while it is unstable for $\phi \in \left[0;1\right] \setminus \left[\underline{\phi}_S;\overline{\phi}_S\right]$;

[16] Lange and Quaas (2007) also obtain partial equilibria, but only for a restricted set of the trade parameter values, whereas Tabuchi and Thisse (2002) find interior equilibria for all values of trade costs, but only under regional asymmetry (i.e., with regions differing in terms of amenity endowment) or worker heterogeneity. Such limitations exclude any realistic application of their model findings to environmental policy analyses.

CP−*iii*: If $\Theta(1)\psi(1)^{1-\varepsilon} \geq 1$, the full agglomeration is a stable equilibrium for a sufficiently high value of trade freeness $\phi \in \left[\phi_S;1\right]$, while it is unstable for $\phi \in \left[0;\phi_S\right]$.

The threshold point ϕ_S (with $\underline{\phi}_S$ and $\overline{\phi}_S$ indicating its upper and lower value in case of existence of multiple points) is the "sustain point" in the sense of Fujita *et al.* (1999). It is implicitly given by any ϕ value that satisfies condition $\Theta(1)\psi(1)^{1-\varepsilon} = \sigma_{\text{CP}}(\phi)$.

(See Appendix *A.1* for a proof).

We can compare our results with those obtained by Lange and Quaas (2007). Even though their model differs from ours in the specification of the negative externalities in the utility function (additive vs. multiplicative), the results of Proposition 1 are comparable with theirs in the absence of the endogenous agglomeration-driving 'market-density' effect. In our analysis this translates into $\psi(1) = 1$. Here only two out of the above three possible outcomes then emerge:[17] *i*) if $\Theta(1) \leq \sigma_{\text{CP}}^{\min}$, the core-periphery structure is unstable independently of freeness of trade (case CP−*i*); and *ii*) if $\Theta(1) > \sigma_{\text{CP}}^{\min}$, two "sustain points" $\underline{\phi}_S$ and $\overline{\phi}_S$ exist and the full agglomeration is a stable equilibrium only for intermediate trade freeness $\phi \in \left[\underline{\phi}_S;\overline{\phi}_S\right]$ (case CP−*ii*). This is identical to Proposition 1 in Lange and Quaas (2007).

III.1.2. Symmetric-spreading pattern in symmetric configurations

The stability conditions of the symmetric spreading equilibrium ($h = 0.5$) are summarized in the following proposition:

PROPOSITION 2: Let the following functions be defined:

[17] Note that case CP−*iii* in Proposition 1 never emerges in the absence of the market density effect because condition $\Theta(1) > 1$ then does not hold.

$$d_{\psi,0} = \frac{4\left(\varepsilon - 1 - \delta\right)}{\delta(\varepsilon - 1)};$$

$$\zeta\left(d_{\psi}^{(0.5)}\right) = \frac{4\gamma\left(\varepsilon - \delta\right)}{\delta a^{f} L} \frac{\left(\varepsilon - \delta\right)}{4 + d_{\psi}^{(0.5)}\left(\varepsilon - 1\right)};$$

$$\zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right) = \zeta\left(d_{\psi}^{(0.5)}\right) + \frac{2\gamma\left(\varepsilon - \delta\right)\left\{4\left(\varepsilon - 1\right) + \varepsilon\left[4 + d_{\psi}^{(0.5)}\left(\varepsilon - 1\right)\right]\right\}^{2}}{\varepsilon\left(\varepsilon - 1\right)^{2} \delta a^{f} L\left[4 + d_{\psi}^{(0.5)}\left(\varepsilon - 1\right)\right]}\cdot$$

$$\cdot\frac{\delta^{2}}{4\delta^{2} + 4\varepsilon\left(\varepsilon - 1\right) + \delta^{2} d_{\psi}^{(0.5)}\left(\varepsilon - 1\right) + \sqrt{\left(\varepsilon^{2} - \delta^{2}\right)\left\{\left[4\left(\varepsilon - 1\right)\right]^{2} - \delta^{2}\left[4 + d_{\psi}^{(0.5)}\left(\varepsilon - 1\right)\right]^{2}\right\}}}.$$

Then stability of the symmetric-spreading equilibrium depends on these functions, where five cases can be distinguished:

SS–*i*: If $d_{\psi}^{(0.5)} > d_{\psi,0}$ and $d_{\Theta}^{(0.5)} < \zeta\left(d_{\psi}^{(0.5)}\right)$, the symmetric-spreading is never a stable equilibrium;

SS–*ii*: If $d_{\psi}^{(0.5)} < d_{\psi,0}$ and $d_{\Theta}^{(0.5)} < \zeta\left(d_{\psi}^{(0.5)}\right)$, a value ϕ_b exists so that the symmetric-spreading is a stable equilibrium for all $\phi \in \left[0;\phi_b\right]$;

SS–*iii*: If $d_{\psi}^{(0.5)} > d_{\psi,0}$ and $d_{\Theta}^{(0.5)} > \zeta\left(d_{\psi}^{(0.5)}\right)$, a threshold value ϕ_b exists so that the symmetric spreading is a stable equilibrium for all $\phi \in \left[\phi_b;1\right]$;

SS–*iv*: If $d_{\psi}^{(0.5)} < d_{\psi,0}$ and $\zeta\left(d_{\psi}^{(0.5)}\right) < d_{\Theta}^{(0.5)} < \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$, two threshold values exist, $\underline{\phi}_b$ and $\overline{\phi}_b$, such that the symmetric equilibrium is stable for all $\phi \in \left[0;\underline{\phi}_b\right] \cup \left[\overline{\phi}_b;1\right]$ and unstable for all $\phi \in \left[\underline{\phi}_b;\overline{\phi}_b\right]$

SS–*v*: If $d_{\psi}^{(0.5)} < d_{\psi,0}$ and $d_{\Theta}^{(0.5)} > \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$, the symmetric-spreading equilibrium is always stable.

The threshold point ϕ_b (whose lower and upper values are represented by $\underline{\phi}_b$ and $\overline{\phi}_b$, respectively) appearing in cases SS–*ii*, SS–*iii* and SS–*iv* is the "break point" in the sense of Fujita *et al.* (1999). It is implicitly given by condition $\sigma_{\mathrm{SS}}(\phi) = 0$.

(See Appendix *A.1* for a proof).

Also here we can compare the results with those obtained by Lange and Quaas (2007), when the endogenous *market density* effect is absent. In our analysis, this comes down to positing $d_{\psi}^{(0.5)} = 0$. Three possible out comes out of the five above presented then arise:[18] *i*) if $d_{\Theta}^{(0.5)} > \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$, the symmetric spreading equilibrium is stable independent of trade freeness (case SS–*v*); *ii*) if $\zeta\left(d_{\psi}^{(0.5)}\right) < d_{\Theta}^{(0.5)} < \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$, two "break points" emerge $\underline{\phi}_b$ and $\overline{\phi}_b$, and the symmetric spreading is a stable equilibrium only for $\phi \in \left[0;1\right] \setminus \left[\underline{\phi}_b;\overline{\phi}_b\right]$ (case SS–*iv*). These two cases correspond to the two possible outcomes mentioned in Proposition 2 in Lange and Quaas (2007), but with other specific analytical conditions due to the difference in the specification of negative externalities in utility. Adopting a multiplicative formulation as we do generates an additional possible outcome that does not emerge in the analysis by Lange and Quaas (2007), namely: *iii*) if $d_{\Theta}^{(0.5)} < \zeta\left(d_{\psi}^{(0.5)}\right)$, a unique "break point" ϕ_b exists and symmetric spreading is a stable equilibrium only for $\phi \in \left[0;\phi_b\right]$ (case SS–*ii*).

III.1.3. Partial agglomeration in symmetric spatial configurations

The existence and stability properties of partial agglomeration (PA) of production ($0.5 < h < 1$) can be derived from those of the core-periphery and symmetric-spreading configurations, as summarized in the following proposition.

PROPOSITION 3: Let us consider a ϕ-value such that $0 \le \phi \le 1$:

PA–*i*: If the core-periphery ($h = 1$) and symmetric spreading ($h = 0.5$) are both stable equilibria for trade barrier ϕ, then a partial agglomeration equilibrium exists which is unstable.

PA–*ii*: If the core-periphery ($h = 1$) and symmetric spreading ($h = 0.5$) are both unstable equilibria for trade barrier ϕ, then a partial agglomeration equilibrium exists which is stable.

(See supplementary material A.1 for a proof).

The emergence and nature (stability vs. instability) of partial agglomeration then depends on the values of $\Theta(1)\psi(1)^{1-\varepsilon}, d_{\psi}^{(0.5)}$ and $d_{\Theta}^{(0.5)}$, which determine the stability ranges of the core-periphery (cases CP–*i* to CP–*iii*) and the symmetric-spreading

[18] Note that cases SS–*i* and SS–*iii* never occur in case of absent market-density effect, since condition $d_{\psi}^{(0.5)} > d_{\psi,0}$ never holds.

equilibria (SS–*i* to SS–*v*), as well as the relative values of "sustain points" and "break points", whenever these exist.

We draw attention to the case in which CP–*i* and SS–*i* are simultaneously satisfied. This results in the instability of both core-periphery and symmetric-spreading equilibria for all trade barriers. According to Proposition 3, this is associated with the stability of partial agglomeration equilibria for all trade barriers ϕ , which represents a continuous asymmetric distributions of the manufacturing sector across regions. Lange and Quaas (2007) already presented an extension of the basic model by Forslid and Ottaviano (2003) that allows for the existence of some stable partial agglomeration equilibria. However, contrary to previous studies in which the existence of such equilibria is always bound to limited ranges of trade barriers, our framework enables stable partial agglomeration equilibria to emerge for all trade barriers.[19] So our model is capable of explaining a wider range of realistic spatial distributions of population and economic activities. What is more, this property makes our framework valuable for policy analysis and overcomes the shortcomings of previous NEG studies, which have seen very little application to policy.

III.2. Equilibrium of non-symmetric spatial configurations.

In this sub-section, we extend the analysis of long term equilibria of the two-region economy to the case of non-symmetric configurations characterized by *ex-ante* differences in terms of *market form* modeled by assuming distinct β-values in the production function: $\beta_1 \neq \beta_2$ [see eq. (4)]. We introduce $\nu = \left(\beta_2 / \beta_1\right)^{1-\varepsilon}$ and, without loss of generality, assume that condition $\nu < 1$ (corresponding to $\beta_1 < \beta_2$) holds.[20] We then investigate the stability conditions of core-periphery ($h = 0$; $h = 1$) and partial agglomeration ($0 < h < 1$).[21]

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[19] See Pfluger (2004) for a review of studies offering stable partial equilibria but under a limited set of trade parameter values.

[20] Since we consider regions with different spatial structures, the indirect utility differential $\Omega(h,\phi)$ takes the general form as given in (19). This holds throughout the subsection.

[21] The symmetric-spreading distribution $h = 0.5$ is not discussed in the context of asymmetric configurations $\left(\beta_1 \neq \beta_2\right)$. The reason is that $\beta_1 \neq \beta_2$ gives $\Omega(0.5,\phi) \neq 0$ [eq. (20)], which does not give an equilibrium.

III.2.1. Core-Periphery pattern in non-symmetric configurations

Similar to the analysis carried out in sub-section *III.1*, we first investigate the conditions under which a full agglomeration of production is a stable equilibrium.

PROPOSITION 4: Given $\Theta(1)$, $\psi(1)$, and $\sigma_{\mathrm{CP}}^{\min} = \frac{\varepsilon - 1}{\varepsilon}\left(\frac{\varepsilon - \delta}{\varepsilon - 1 + \delta}\right)^{\frac{1}{2}\left(\frac{\delta}{\varepsilon - 1}+1\right)}\left(\frac{\varepsilon - 1 - \delta}{\varepsilon + \delta}\right)^{\frac{1}{2}\left(\frac{\delta}{\varepsilon - 1}-1\right)}$, three cases must be distinguished according to the position of $\Theta(1)\psi(1)^{1-\varepsilon}$ with respect to $\sigma_{\mathrm{CP}}^{\min}$ and 1:

CP'–*i*: If $\frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon} \leq \sigma_{\mathrm{CP}}^{\min}$, the full agglomeration $h = 1$ is never an equilibrium, whatever the value of trade freeness;

CP'–*ii*: If $\sigma_{\mathrm{CP}}^{\min} < \frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon} < 1$, the full agglomeration $h = 1$ is a stable equilibrium for intermediate trade freeness $\phi \in \left[\underline{\phi}_S^{\,*};\overline{\phi}_S^{\,*}\right]$, while it is unstable for $\phi \in \left[0;1\right] \setminus \left[\underline{\phi}_S^{\,*};\overline{\phi}_S^{\,*}\right]$;

CP'–*iii*: If , the full agglomeration $h = 1$ is a stable equilibrium for a sufficiently high value of trade freeness $\phi \in \left[\phi_S^{\,*};1\right]$, while it is unstable for $\phi \in \left[0;\phi_S^{\,*}\right]$;

The threshold point $\phi_S^{\,*}$ (with $\underline{\phi}_S^{\,*}$ and $\overline{\phi}_S^{\,*}$ indicating its upper and lower value in case of existence of multiple points) is the "sustain point" in the sense of Fujita *et al.* (1999). It is implicitly given by any value of ϕ that satisfies the condition $\frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon} = \sigma_{\mathrm{CP}}(\phi)$.

(See Appendix *A.2* for a proof).

Similarly we derive the stability condition for the full agglomeration $h = 0$.

PROPOSITION 5: Given $\Theta(1)$, $\psi(1)$, and $\sigma_{\mathrm{CP}}^{\min} = \frac{\varepsilon-1}{\varepsilon}\left(\frac{\varepsilon-\delta}{\varepsilon-1+\delta}\right)^{\frac{1}{2}\left(\frac{\delta}{\varepsilon-1}+1\right)}\left(\frac{\varepsilon-1-\delta}{\varepsilon+\delta}\right)^{\frac{1}{2}\left(\frac{\delta}{\varepsilon-1}-1\right)}$,

three cases must be distinguished according to the position of $\Theta(1)\psi(1)^{1-\varepsilon}$ with respect to $\sigma_{\mathrm{CP}}^{\min}$ and 1:

CP "–*i*: If $\nu\Theta(1)\psi(1)^{1-\varepsilon} \leq \sigma_{\mathrm{CP}}^{\min}$, the full agglomeration $h=1$ is never an equilibrium, whatever the trade freeness;

CP "–*ii*: If $\sigma_{\mathrm{CP}}^{\min} < \nu\Theta(1)\psi(1)^{1-\varepsilon} < 1$, the full agglomeration $h=1$ is a stable equilibrium for intermediate trade freeness $\phi \in \left[\underline{\phi}_S^{**};\overline{\phi}_S^{**}\right]$, while it is unstable for $\phi \in \left[0;1\right] \setminus \left[\underline{\phi}_S^{**};\overline{\phi}_S^{**}\right]$;

CP "–*iii*: If $\nu\Theta(1)\psi(1)^{1-\varepsilon} \geq 1$, the full agglomeration $h=1$ is a stable equilibrium for a sufficiently high value of trade freeness $\phi \in \left[\phi_S^{**};1\right]$, while it is unstable for $\phi \in \left[0;\phi_S^{**}\right]$;

The threshold point ϕ_S^{**} (with $\underline{\phi}_S^{**}$ and $\overline{\phi}_S^{**}$ indicating its upper and lower value in case multiple points exist) is the "sustain point" in the sense of Fujita *et al.* (1999). It is implicitly given by any ϕ value that satisfies the condition $\frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon} = \sigma_{\mathrm{CP}}(\phi)$.

(See Appendix *A.2* for a proof).

Two characteristics of the full-agglomeration equilibria are worth noting. First, whatever the ν-value, a full agglomeration is *never* an equilibrium for $\phi = 0$ ("no black hole" condition). Second, by assuming $\nu < 1$, condition $\Theta(1)\psi(1)^{1-\varepsilon} > \nu\sigma_{\mathrm{CP}}(\phi)$ is less stringent than condition $\Theta(1)\psi(1)^{1-\varepsilon} > \frac{1}{\nu}\sigma_{\mathrm{CP}}(\phi)$, so that the stability range of $h=1$ (indicating full agglomeration in region 1) is wider than the stability range of $h=0$ (indicating full agglomeration in region 2). This makes sense since positing $\nu < 1$ means that region 1 is characterized by a stronger *market density* effect than region 2 (as captured by $\beta_1 < \beta_2$), which fosters agglomeration of production though a decrease in the production costs.

III.2.2. Partial agglomeration in the non-symmetric spatial configuration

The equilibrium properties of partial agglomeration (PA) of production ($0 < h < 1$) can be derived from those of the core-periphery configurations ($h = 0$ and $h = 1$) as summarized in the following proposition:

PROPOSITION 6: Let us consider a ϕ-value with $0 \leq \phi \leq 1$:

PA'–*i*: If $h = 0$ and $h = 1$ are both stable equilibria for trade barrier ϕ, then an unstable partial agglomeration equilibrium exists.

PA'–*ii*: If $h = 0$ and $h = 1$ are both unstable equilibria for trade barrier ϕ, then a stable partial agglomeration equilibrium exists.

(See Appendix *A.2* for a proof).

According to Proposition 6, if both $h = 1$ and $h = 0$ are never stable equilibria, a stable partial agglomeration equilibrium arises for all trade barrier values. This situation occurs when $\Theta(1)\psi(1)^{1-\varepsilon} \leq \nu\sigma_{\text{CP}}^{\min}$.

III.3. Interpretation of market density and environmental effects as the drivers of the equilibria

The analytical equilibrium conditions derived in the two previous sections complete the earlier NEG literature. The impact of those two effects on long-term equilibria depends on their relative intensities, as defined by functions ψ and Θ, respectively.[22]

Let us start with the stability range of the core-periphery pattern. Everything else being equal, a stronger *market density* effect, as captured by a lower $\psi(1)$, favors agglomeration by widening the range of trade freeness compatible with stability of the core-periphery,[23] whereas a stronger environmental effect as captured by a lower $\Theta(1)$ fosters dispersion by narrowing this range. The three cases discussed in Proposition 1 differ in terms of the stability range of full agglomeration equilibrium resulting from the interplay between the *market density* and environmental effects. In the case of CP–*i*, there is no "sustain point": the centrifugal environmental effect is

[22] For the sake of clarity of interpretation of the results, we abstract from considering *ex-ante* differences among regions as in non-symmetric configurations, which, although affecting the results, do not modify the qualitative effects at play.

[23] We recall that $1-\varepsilon < 0$, so that a lower $\psi(1)$ means a higher $\psi(1)^{1-\varepsilon}$.

so strong that it always renders full agglomeration unstable. The case CP–*ii* corresponds to an intermediate situation in which centrifugal and centripetal forces associated with *market density* and environmental effects, respectively, are of the same order of magnitude and offset each other. The boundary case $\Theta(1)\psi(1)^{1-\varepsilon} = 1$ corresponds to a situation in which the centrifugal environmental and the centripetal *market density* forces fully offset each other, and lead to an identical result as in the traditional "footloose entrepreneur" model where they are absent: the "sustain point" ϕ_S is unique and is defined by condition $\sigma_{\mathrm{CP}}\left(\phi\right) = 1$, which is identical to condition (25) in Forslid and Ottaviano (2003). Finally, in case CP–*iii* is associated with a unique "sustain point": the centripetal impact of the *market density* effect dominates, making core-periphery a stable equilibrium in the case of free trade $\phi = 1$, so that the range of stability is given by $\phi \in \left[\phi_S;1\right]$.

We now turn to consider the stability of the symmetric spreading equilibrium. As formalized in the decomposition of $\sigma_{\mathrm{SS}}(\phi)$ in (A-6), our model accounts for the relative importance of *market density* and environmental effects, as well as for their dependence on the long-run trade costs, as captured by $\sigma_{\mathrm{SS}}^{(\psi)}(\phi)$ and $\sigma_{\mathrm{SS}}^{(\Theta)}(\phi)$ respectively. Given the relevance and the novelty of this analysis we take the next step of analytically deriving the conditions under which both the interplaying and the trade-dependence mechanisms occur. Due to limited space, we summarize here the main insights from this analysis; mathematical details are given in Appendix *A.3*.

The first term on the right-hand side of (A-6), ${}^{(\mathrm{FE})}\sigma_{\mathrm{SS}}(\phi)$, captures the forces at play in the traditional footloose-entrepreneur model, as developed by Forslid and Ottaviano (2003), in the absence of any agglomeration and environmental effects ($d_{\psi}^{(0.5)} = d_{\Theta}^{(0.5)} = 0$). In this case, the stability range of the symmetric-spreading equilibrium is determined by condition ${}^{(\mathrm{FE})}\sigma_{\mathrm{SS}}(\phi) < 0$. With (A-7), this means $\phi < \dfrac{\left(\varepsilon - \delta\right)\left(\varepsilon - 1 - \delta\right)}{\left(\varepsilon + \delta\right)\left(\varepsilon - 1 + \delta\right)}$, an identical expression to condition (26) obtained by Forslid and Ottaviano (2003).

The last two terms on the right-hand side of (A-6) describe how *market density* and environmental effects influence the stability of the symmetric-spreading equilibrium. The second (third) term is positive (negative) [see eq. (A-7)], so that the *market density* (environmental) effect unequivocally contributes to the instability (stability) of the symmetric-spreading configuration. A more intense *market density* (environmental) effect, as captured by a higher $d_{\psi}^{(0.5)}$ ($d_{\Theta}^{(0.5)}$), results in a narrowing (widening) of the stability range of the symmetric-spreading equilibrium.

Proposition 2 provides explicit conditions for long-term equilibria in function of the intensity of the *market density* and environmental effects $d_{\psi}^{(0.5)}$ and $d_{\Theta}^{(0.5)}$; these conditions can be interpreted in terms of the strength of these effects. The high value of $d_{\psi}^{(0.5)}$ in condition $d_{\psi}^{(0.5)} > d_{\psi,0}$ can be viewed as a 'strong *market density* effect'. Next, $d_{\Theta}^{(0.5)} > \zeta\left(d_{\psi}^{(0.5)}\right)$ means a strong centrifugal force, which we will refer to as a 'strong environmental effect'. Moreover, since $\zeta\left(d_{\psi}^{(0.5)}\right) < \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$, condition $d_{\Theta}^{(0.5)} > \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$ is more restrictive than $d_{\Theta}^{(0.5)} > \zeta\left(d_{\psi}^{(0.5)}\right)$on the value of $d_{\Theta}^{(0.5)}$. Therefore, we interpret the first condition, $d_{\Theta}^{(0.5)} > \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$, as representing a 'very strong environmental effect'.

To better understand how the interplay between the *market density* and environmental effects influences the existence and nature of equilibria, let us give an economic interpretation of the five conditions in Proposition 2. We first consider the situation where both *market density* and environmental effects are weak, as captured by $d_{\psi}^{(0.5)} < d_{\psi,0}$ and $d_{\Theta}^{(0.5)} < \zeta\left(d_{\psi}^{(0.5)}\right)$. This corresponds to case SS–*ii* in Proposition 2. This type of stability condition is similar to the one obtained in the traditional footloose-entrepreneur model (Forslid and Ottaviano, 2003). This similarity makes sense, since the addition of small *market density* and environmental effects only marginally modifies the stability conditions that hold without these effects. We then turn to the case of a strong environmental and a weak *market density* effect, as captured by conditions $d_{\psi}^{(0.5)} < d_{\psi,0}$ and $d_{\Theta}^{(0.5)} > \zeta\left(d_{\psi}^{(0.5)}\right)$. Two sub-cases must be distinguished:

- If condition $\zeta\left(d_{\psi}^{(0.5)}\right) < d_{\Theta}^{(0.5)} < \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$ holds, the environmental effect is strong but not 'very strong', and a range of high ϕ-values (close to 1) appears, for which the centrifugal environmental effect is strong enough to favor stability of the symmetric spreading, contrary to the outcome of the traditional footloose-entrepreneur model. As a result, the symmetric-spreading pattern is stable for high and low trade barriers, while it remains unstable for intermediate trade barriers. This corresponds to case SS–*iv* in Proposition 2;

- If condition $d_{\Theta}^{(0.5)} > \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$ holds, i.e. the environmental effect is 'very strong', the associated centrifugal force dominates and uniformly favors the stability of the symmetric-spreading equilibrium. This corresponds to case SS–*v* in Proposition 2 with the symmetric-spreading equilibrium being stable for all values of the trade barrier.

All cases in which condition $d_{\psi}^{(0.5)} > d_{\psi,0}$ holds correspond to a strong *market density* effect which fosters the instability of the symmetric-spreading equilibrium. The magnitude of the environmental effect, which tends to counterbalance agglomeration, determines the resulting net equilibrium. If a weak environmental effect is assumed [with $d_{\Theta}^{(0.5)} < \zeta\left(d_{\psi}^{(0.5)}\right)$], the *market density* effect dominates the location decisions of economic agents and leads to the instability of the symmetric spreading under all values of the trade barrier (case SS–*i* in Proposition 2). If, on the contrary, a strong environmental effect is considered [as from $d_{\Theta}^{(0.5)} > \zeta\left(d_{\psi}^{(0.5)}\right)$], the trade-off between *market density* and environmental effect dominates the stability conditions of the symmetric-spreading equilibrium.

It is found that the positive *market density* (negative environmental) effect dominates at low (high) ϕ-values, leading to the instability (stability) of the symmetric-spreading equilibrium (see Appendix *A.3* for a proof). This corresponds to case SS–*iii* in Proposition 2.

III.4. Spatial equilibria

Combining the conditions that define the nature of the long-run equilibria presented in previous sub-sections gives rise to several alternative types of bifurcation diagrams. For the sake of realistically representing the spatial organization of the world economy, we exclude in the remainder of the paper the extreme equilibria that one would not expect to find in practice. In particular, we limit the analysis to equilibria other than full agglomeration, and instead focus on those equilibria that allow for a (stable) partial agglomeration to arise. To achieve this, we adopt adequate numerical values of model parameters and exogenous variables, as well as the functional specifications, whose rationale is discussed in Appendices *A.4* and *A.5*, respectively.

We start by considering stable (blue curves) and unstable (green curves) equilibria in the symmetric configurations A and B, as defined by condition (18) in the case $\beta_1 = \beta_2$ (see Figure I). The emergence of partial equilibria with identical regions is not a novelty in the NEG literature but they are traditionally either unstable–as in the seminal paper by Krugman (1991) and in section 3 of Forslid and Ottaviano (2003), when symmetric unskilled labor endowment is assumed–or only stable for a limited range of trade barriers (see Lange and Quaas, 2007). Here, on the contrary, symmetric configurations with identical regions prove to generate partial equilibria for *all* trade barriers.

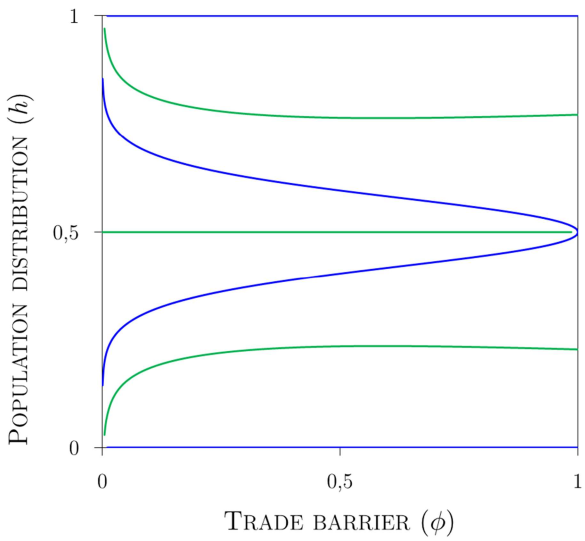

Figure I: Long-run equilibria for symmetric spatial configurations.

Figure II displays long-run stable (blue curve) and unstable (green curve) equilibria for the asymmetric configuration C, as defined by condition (18) in the case $\beta_1 \neq \beta_2$. Again, partial agglomeration equilibria emerge for any trade barrier. However, unlike in the previous case, the partial agglomeration equilibria are not symmetric around $h = 0.5$, as a consequence of *ex-ante* differences between the two regions in the spatial setting. More precisely, a partial agglomeration in the (urbanized) region 1 ($0.5 < h < 1$) can be a long-run equilibrium for any trade barrier, while a partial agglomeration in the (undeveloped) region 2 ($0 < h < 0.5$) can be a long-run equilibrium only for sufficiently high trade barriers. Firms may indeed agglomerate in the undeveloped region only if high trade costs ensure a strong incentive for a relocation of production close to consumption places. Here again, this emergence of stable partial equilibria in a non-symmetric configuration is not a novelty. See, for example, section 4 of Forslid and Ottaviano (2003), where exogenous differences between regions are introduced. A crucial new feature of our paper is the generalization of this result for *all* trade barriers.

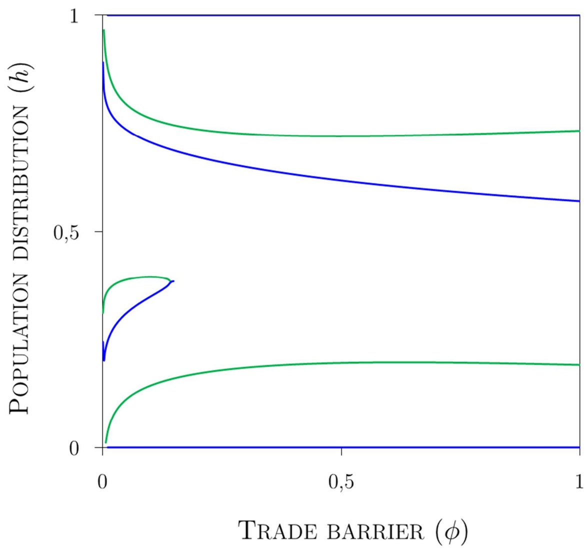

Figure II: Long-run equilibria for the asymmetric spatial configuration.

IV. Conclusion

This paper has developed a theoretical approach to study the impacts of agglomeration spillovers on the welfare of the economy in the presence of local and global environmental externalities. The approach accounts for three factors contributing to economic welfare, namely agglomeration effects, advantages of trade, and environmental externalities. It extends the "footloose entrepreneur" model of the new economic geography by introducing a number of new features.

The major innovation was the introduction of an additional endogenous agglomeration factor which we refer to as the "market density" effect. This allows the model to simultaneously address increasing returns to scale at the firm level and external economies at the industry level. Moreover, with this set-up we explicitly formalized heterogeneous patterns of land use and development of the regional economies (which we call 'spatial configurations'). Next, we illustrated how the model can be extended with global and stock pollutants. This allows for addressing environmental policy concerns as well as connecting the NEG literature with the existing literatures on trade and environment (which use a distinct theoretical framework). A number of additional, minor features were introduced that remove some limitations of the NEG approach. The resulting overall framework can deal with policy questions about sustainable and efficient use of space and natural resources.

The starting point of our analysis was a spatial-economic structure which includes manufacturing and traditional production sectors. Regions are characterized by alternative degrees of land development resulting in potentially different levels of agglomeration spillovers. Through the market density effect, agglomeration affects environmental pollution. Two particular mechanisms are relevant here. First, agglomeration increases the scale of production activity leading to more energy use and associated pollutive emissions. Second, agglomeration reduces energy requirements for production through lower learning and R&D spillovers leading to improved energy technologies (i.e. lower emissions). Because of these opposite mechanisms, the interplay between trade and agglomeration in determining a stable spatial distribution of economic activity is not trivial, that is, the net general equilibrium outcome is not obvious ex-ante.

The model extends previous NEG studies by deriving analytical conditions that enable continuous and asymmetric distributions of population and economic activity across space when the environmental and agglomeration externalities are accounted for, and this for the whole range of trade costs (possibly partly due to trade policies). This makes it very suitable for addressing the spatial economic and trade dimensions of environmental problems and moreover paves the way for further policy-relevant applications.

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Appendix

A1. Long-run equilibrium conditions for symmetric spatial configurations

For symmetric spatial configurations defined by $\beta_1 = \beta_2$, the indirect utility in (19) and the function in (20) can be rewritten as follows:

$$\text{(A-1)}\quad \Omega(h,\phi) = \frac{\Gamma'}{\beta^{\delta}} \frac{\omega(h,\phi)}{\phi\left[h^2\psi(h)^{2(1-\varepsilon)} + (1-h)^2\psi(1-h)^{2(1-\varepsilon)}\right] + \left[1-\frac{\delta}{\varepsilon}+\phi^2\left(1+\frac{\delta}{\varepsilon}\right)\right]h(1-h)\psi(h)^{1-\varepsilon}\psi(1-h)^{1-\varepsilon}}, \text{ and}$$

$$\text{(A-2)}\quad \begin{aligned}\omega(h,\phi) = {} & \frac{\psi(h)^{1-\varepsilon}\left\{2h\phi\psi(h)^{1-\varepsilon} + \left[1-\frac{\delta}{\varepsilon}+\phi^2\left(1+\frac{\delta}{\varepsilon}\right)\right](1-h)\psi(1-h)^{1-\varepsilon}\right\}}{\left[h\psi(h)^{1-\varepsilon} + \phi(1-h)\psi(1-h)^{1-\varepsilon}\right]^{\frac{\delta}{1-\varepsilon}}}\Theta(h,\phi) + \\ & - \frac{\psi(1-h)^{1-\varepsilon}\left\{2\phi(1-h)\psi(1-h)^{1-\varepsilon} + \left[1-\frac{\delta}{\varepsilon}+\phi^2\left(1+\frac{\delta}{\varepsilon}\right)\right]h\psi(h)^{1-\varepsilon}\right\}}{\left[h\phi\psi(h)^{1-\varepsilon} + (1-h)\psi(1-h)^{1-\varepsilon}\right]^{\frac{\delta}{1-\varepsilon}}}\Theta(1-h,\phi).\end{aligned}$$

A1.1. Core-periphery pattern ($h = 1$)

Rewriting equation (A-2) for the case of a Core-Periphery (CP) pattern ($h = 1$) and recalling that $\Theta(0) = 1$ and $\psi(0) = 1$, we obtain:[24]

[24]Deriving $E_j^L(1)$ from (10), (12), (12*bis*) and (13) shows that the pollution flow function is independent from ϕ for $h = 1$. Hence the index ϕ in $\Theta(1)$ can be omitted.

(A-3) $$\omega(1,\phi)=\frac{\psi(1)^{1-\varepsilon}}{\left[\psi(1)^{1-\varepsilon}\right]^{\frac{\delta}{1-\varepsilon}}}\left\{2\phi\Theta(1)\psi(1)^{1-\varepsilon}-\frac{\left[1-\frac{\delta}{\varepsilon}+\phi^2\left(1+\frac{\delta}{\varepsilon}\right)\right]\Theta(0)\psi(0)^{1-\varepsilon}}{\phi^{\frac{\delta}{1-\varepsilon}}}\right\}.$$

Combining (A-3) with the condition (18-*b*), and recalling that $\Theta(0)=1$ and $\psi(0)=1$, we find that the core-periphery pattern ($h=1$) is a stable equilibrium if and only if $\Theta(1)\psi(1)^{1-\varepsilon}\geq\sigma_{\text{CP}}(\phi)$, where:

(A-4) $$\sigma_{\text{CP}}(\phi)=\frac{1-\frac{\delta}{\varepsilon}+\phi^2\left(1+\frac{\delta}{\varepsilon}\right)}{2\left(\phi\right)^{1+\frac{\delta}{1-\varepsilon}}}.$$

This a concave function that defines the stability condition of the core-periphery equilibrium pattern in the case of symmetric configurations, as summarized by the following condition:

CONDITION 1: Given $\sigma_{\text{CP}}(\phi)$ in *III.1* and (A.4), the core-periphery pattern $h=1$ is a stable equilibrium for a trade barrier ϕ (with $0\leq\phi\leq1$) if and only if:
$\Theta(1)\psi(1)^{1-\varepsilon}\geq\sigma_{\text{CP}}(\phi)$.[25]

The proof of Proposition 1 follows:

PROOF OF PROPOSITION 1**:** From (A-4) we obtain that:
$\frac{\partial\sigma_{\text{CP}}}{\partial\phi}=\frac{\left(1+\frac{\delta}{\varepsilon}\right)\left(1+\frac{\delta}{\varepsilon-1}\right)\left(\phi^2-\phi_m^2\right)}{2\phi^{2+\frac{\delta}{\varepsilon-1}}}$; with: $\phi_m=\sqrt{\frac{\left(\varepsilon-\delta\right)\left(\varepsilon-1-\delta\right)}{\left(\varepsilon+\delta\right)\left(\varepsilon-1+\delta\right)}}$. The value is then negative for $\phi<\phi_m$, while it is positive for $\phi>\phi_m$. This leads to σ_{CP} being decreasing for $\phi<\phi_m$ while increasing for $\phi>\phi_m$. The σ_{CP} function reaches its minimum at $\phi=\phi_m$, and the minimum value $\sigma_{\text{CP}}^{\min}$ of $\sigma_{\text{CP}}(\phi)$ is given by $\sigma_{\text{CP}}(\phi_m)$:

[25] Stability of long-run equilibrium in a NEG model requires that the additional so-called "no black hole" condition is satisfied, which imposes that the full agglomeration is never a stable equilibrium in case of autarky $\phi=0$ (Fujita *et al.*, 1999). According to Condition 1, this means ensuring that function $\sigma_{\text{CP}}(\phi)$ tends to infinity when $\phi=0$, which, from calculations in *III.A*, is in turn equivalent to $1+\delta/(1-\varepsilon)>0$. This analytical form for the "no black hole" condition is similar to the one obtained in Forslid and Ottaviano (2003), and is supposed to hold in the reminder of the paper.

$$\sigma_{CP}^{min} = \frac{\varepsilon - 1}{\varepsilon}\left(\frac{\varepsilon - \delta}{\varepsilon - 1 + \delta}\right)^{\frac{1}{2}\left(\frac{\delta}{\varepsilon-1}+1\right)}\left(\frac{\varepsilon - 1 - \delta}{\varepsilon + \delta}\right)^{\frac{1}{2}\left(\frac{\delta}{\varepsilon-1}-1\right)}.$$

In addition, $\lim_{\phi\to 0}\sigma_{CP}(\phi) = +\infty$ and $\sigma_{CP}(\phi = 1) = 1$. Figure A.1 gives a graphical illustration of $\sigma_{CP}(\phi)$.

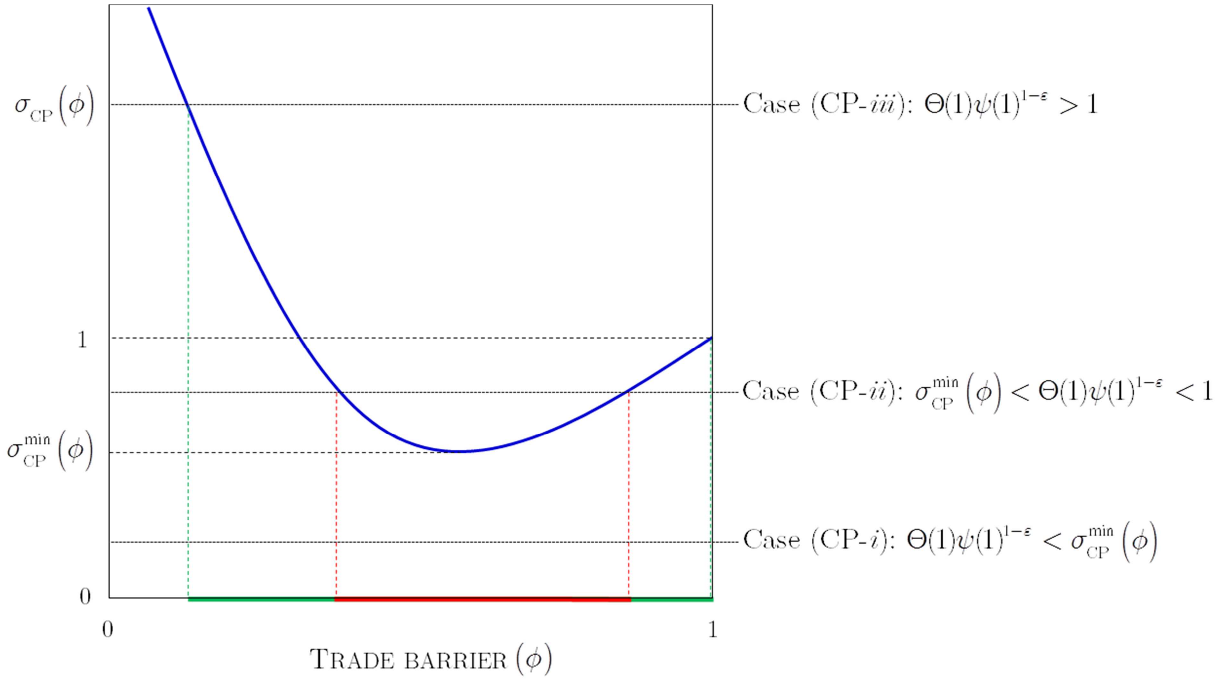

Figure A1: Graphical illustration of the core-periphery pattern: 3 cases

According to Condition 1, the stability pattern of the core-periphery depends on the value of $\Theta(1)\psi(1)^{1-\varepsilon}$:

- If $\Theta(1)\psi(1)^{1-\varepsilon} < \sigma_{CP}^{min}$, then we have $\Theta(1)\psi(1)^{1-\varepsilon} < \sigma_{CP}(\phi)$ for any ϕ. According to Condition 1, this means that the core-periphery is never an equilibrium. This corresponds to case CP–*i* in Proposition 1;
- If $\sigma_{CP}^{min} < \Theta(1)\psi(1)^{1-\varepsilon} < 1$, then there exist two ϕ-values over $\phi \in [0;1]$ such that $\Theta(1)\psi(1)^{1-\varepsilon} = \sigma_{CP}(\phi)$. By noting these $\underline{\phi}_s$ and $\overline{\phi}_s$, the condition $\Theta(1)\psi(1)^{1-\varepsilon} > \sigma_{CP}(\phi)$ is satisfied if and only if $\phi \in \left[\underline{\phi}_s;\overline{\phi}_s\right]$. According to Condition 1, this means that the core-periphery is an equilibrium if and only if $\phi \in \left[\underline{\phi}_s;\overline{\phi}_s\right]$. This corresponds to case CP–*ii* in Proposition 1;
- If $\Theta(1)\psi(1)^{1-\varepsilon} > 1$, then there exist only one ϕ-value in the interval $\phi \in [0;1]$ such that $\Theta(1)\psi(1)^{1-\varepsilon} = \sigma_{CP}(\phi)$. By noting this value $\underline{\phi}_s$, the condition

$\Theta(1)\psi(1)^{1-\varepsilon} > \sigma_{\text{CP}}(\phi)$ is satisfied if and only if $\phi \in \left[\underline{\phi}_s;1\right]$. According to Condition 1, this means that the core-periphery is an equilibrium if and only if $\phi \in \left[\underline{\phi}_s;1\right]$. This corresponds to case CP–*iii* in Proposition 1.

This concludes the proof.

A1.2. Symmetric spreading ($h = 0.5$)

We consider the stability range of the core-periphery equilibrium $h = 0.5$. Rewriting (20) for this specific case shows that $\omega(0.5,\phi) = 0$ for any ϕ, so that the symmetric outcome is always an equilibrium. Such an equilibrium is stable if and only if $\frac{\partial \Omega}{\partial h}(0.5,\phi) \le 0$. Using (A-1) and (A-2) we can derive:

$$\text{(A-5)}\quad \frac{\partial \Omega}{\partial h}\left(0.5,\phi\right) = \sigma_{\text{SS}}(\phi)\frac{\left[\frac{1}{\alpha}\left(\frac{\varepsilon\gamma}{\varepsilon-1}\right)^{1-\delta}\right]\Theta(0.5,\phi)2^{1-\frac{\delta}{\varepsilon-1}}L\delta\left[\beta^{1-\varepsilon}(1+\phi)\psi(0.5)^{\frac{\delta}{\varepsilon-1}}\right]}{\left(\varepsilon-\delta\right)\left(\phi+1\right)\left[\delta\left(\phi-1\right)+\varepsilon\left(\phi+1\right)\right]},$$

where $\sigma_{\text{SS}}(\phi)$ can be decomposed into three components:

$$\text{(A-6)}\qquad \sigma_{\text{SS}}(\phi) = {}^{\text{(FE)}}\sigma_{\text{SS}}(\phi) + d_{\psi}^{(0.5)}\sigma_{\text{SS}}^{(\psi)}(\phi) - d_{\Theta}^{(0.5)}\sigma_{\text{SS}}^{(\Theta)}(\phi),$$

with

$$\begin{aligned}
&{}^{\text{(FE)}}\sigma_{\text{SS}}(\phi) = 2\left(1-\phi\right)\left[\varepsilon+\delta+\frac{\delta}{\varepsilon-1}\left(\delta+\varepsilon\right)\right]\left[\phi-\frac{\varepsilon-\delta}{\varepsilon+\delta}\frac{\varepsilon-1-\delta}{\varepsilon-1+\delta}\right];\\
\text{(A-7)}\quad &\sigma_{\text{SS}}^{(\psi)}(\phi) = \frac{1}{2}\left\{-\delta\phi^2\left(\varepsilon+\delta\right)+\phi\left[4\varepsilon\left(\varepsilon-1\right)+2\delta^2\right]+\delta\left(\varepsilon-\delta\right)\right\};\\
&\sigma_{\text{SS}}^{(\Theta)}(\phi) = \frac{\delta\varepsilon a^f L\left(\varepsilon-1\right)}{\gamma\left(\varepsilon-\delta\right)}\phi\left(2+d_{\psi}^{(0.5)}\frac{\varepsilon-1}{2}\right).
\end{aligned}$$

Here we introduce $d_{\psi}^{(0.5)} = -2\frac{\psi'(0.5)}{\psi(0.5)}$ and $d_{\Theta}^{(0.5)} = -2\frac{\frac{\partial\Theta}{\partial E}(0.5)}{\Theta(0.5)}$, which can be interpreted as measures of the intensity of the agglomeration and the environmental effects at $h = 0.5$, respectively.[26] Since all other terms on the right-hand side of equation (A-5) are positive, $\frac{\partial \Omega}{\partial h}\left(0.5, \phi\right)$ has the same sign as $\sigma_{SS}(\phi)$. The stability condition of the symmetric-spreading equilibrium in symmetric configurations can then be expressed as follows:

CONDITION 2: A symmetric distribution of skilled workers ($h = 0.5$) is always an equilibrium. Given (A-5), such an equilibrium is stable if and only if $\sigma_{SS}(\phi) < 0$.

The proof of Proposition 2 is then obtained by analyzing the sign of $\sigma_{SS}(\phi)$ from (A-6) and (A-7):

PROOF OF PROPOSITION 2**:** From equation (A-6), σ_{SS} can be rewritten as a second-order polynomial in ϕ, as follows: $\sigma_{SS}(\phi) = a_0 + a_1\phi + a_2\phi^2$. Coefficients a_0, a_1, a_2 can be expressed in terms of the constants of the model δ, ε, a^f, m^f, L and the intensity of the agglomeration and environmental effects $d_\psi^{(h=0.5)}$ and $d_\Theta^{(h=0.5)}$:

$$a_0 = \frac{\left(\varepsilon - \delta\right)\left[d_\psi^{(h=0.5)}\delta\left(\varepsilon - 1\right) - 4\left(\varepsilon - 1 - \delta\right)\right]}{2\left(\varepsilon - 1\right)};$$

$$a_1 = \frac{4\delta^2 + 4\varepsilon\left(\varepsilon - 1\right)}{\varepsilon - 1} + d_\psi^{(h=0.5)}\left[\delta^2 + 2\varepsilon\left(\varepsilon - 1\right)\right] - d_\Theta^{(h=0.5)}\frac{\delta a^f L\varepsilon\left(\varepsilon - 1\right)}{2\gamma\left(\varepsilon - \delta\right)}\left(4 + d_\psi^{(h=0.5)}\left(\varepsilon - 1\right)\right);$$

$$a_2 = -\frac{\left(\varepsilon + \delta\right)\left[d_\psi^{(h=0.5)}\delta\left(\varepsilon - 1\right) + 4\left(\varepsilon - 1 + \delta\right)\right]}{2\left(\varepsilon - 1\right)}.$$

The coefficient a_2 of the polynomial $\sigma_{SS}\left(\phi\right)$ is negative, so that $\sigma_{SS}\left(\phi\right)$ is a concave function. The sign of $\sigma_{SS}\left(\phi\right)$ over $\phi \in \left[0;1\right]$ is dependent on its signs at $\phi = 0$ and $\phi = 1$. Four cases must be distinguished:

1) If $\sigma_{SS}\left(0\right) > 0$ and $\sigma_{SS}\left(1\right) > 0$, the concave polynomial $\sigma_{SS}\left(\phi\right)$ remains positive over the whole range $\phi \in \left[0;1\right]$;

[26] Deriving $E_j^L(0.5)$ from (10), (12), (12*bis*) and (13) shows that $E_j^L(0.5)$ is independent of ϕ for $h = 0.5$. Hence, the index ϕ in $\Theta(0.5)$ and in $d_\Theta^{(0.5)}$ can be omitted. Moreover, since ψ and Θ are both decreasing in *h*, their derivatives are negative. Consequently, $d_\psi^{(0.5)}$ and $d_\Theta^{(0.5)}$ are positive terms.

2) If $\sigma_{SS}(0) < 0$ and $\sigma_{SS}(1) > 0$, the polynomial $\sigma_{SS}(\phi)$ has a single root ϕ_b over $\phi \in [0;1]$; $\sigma_{SS}(\phi)$ is negative over $\phi \in [0;\phi_b]$, while positive over $\phi \in [\phi_b;1]$;
3) If $\sigma_{SS}(0) > 0$ and $\sigma_{SS}(1) < 0$, the polynomial $\sigma_{SS}(\phi)$ has a single root ϕ_b over $\phi \in [0;1]$; $\sigma_{SS}(\phi)$ is positive over $\phi \in [0;\phi_b]$, while negative over $\phi \in [\phi_b;1]$;
4) If $\sigma_{SS}(0) < 0$ and $\sigma_{SS}(1) < 0$, the polynomial $\sigma_{SS}(\phi)$ has either zero or two roots according to the sign of the discriminant $\Delta = a_1^2 - 4a_0a_2$:
    a) If $\Delta > 0$, $\sigma_{SS}(\phi)$ has two roots $\underline{\phi}_b$ and $\overline{\phi}_b$ ($\underline{\phi}_b < \overline{\phi}_b$); $\sigma_{SS}(\phi)$ is positive $\phi \in [\underline{\phi}_b;\overline{\phi}_b]$, while negative for $\phi < \underline{\phi}_b$ and $\phi > \overline{\phi}_b$. It can be demonstrated that for $0 < \underline{\phi}_b < \overline{\phi}_b < 1$:
        i. $\Delta > 0$ leads to $\dfrac{\partial \sigma_{SS}}{\partial \phi}(0) > 0$. With $\sigma_{SS}(0) < 0$, this means that $\underline{\phi}_b > 0$;
        ii. $\sigma_{SS}(1) < 0$ leads to $\dfrac{\partial \sigma_{SS}}{\partial \phi}(1) < 0$. With $\sigma_{SS}(1) < 0$, this means $\overline{\phi}_b < 1$.

    Then, $\sigma_{SS}(\phi)$ is positive over $\phi \in [\underline{\phi}_b;\overline{\phi}_b]$, while negative over $\phi \in [0;1] \setminus [\underline{\phi}_b;\overline{\phi}_b]$;
    b) If $\Delta < 0$, $\sigma_{SS}(\phi)$ has no root and remains negative over the whole range $\phi \in [0;1]$
    c) From eq. (A-6) and (A-7) it follows that:

$$\sigma_{SS}(0) > 0 \Leftrightarrow d_\psi^{(0.5)} > d_{\psi,0};$$
$$\sigma_{SS}(1) > 0 \Leftrightarrow d_\Theta^{(0.5)} < \zeta\left(d_\psi^{(0.5)}\right);$$
$$\Delta > 0 \Leftrightarrow d_\Theta^{(0.5)} < \zeta_\Delta\left(d_\psi^{(0.5)}\right),$$

where the symbols denote the following mathematical expressions:

$$d_{\psi,0} = \frac{4\left(\varepsilon - 1 - \delta\right)}{\delta(\varepsilon - 1)};$$

$$\zeta\left(d_{\psi}^{(0.5)}\right) = \frac{4\gamma\left(\varepsilon - \delta\right)}{\delta a^{f} L} \frac{\left(\varepsilon - \delta\right)}{4 + d_{\psi}^{(0.5)}\left(\varepsilon - 1\right)};$$

$$\zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right) = \zeta\left(d_{\psi}^{(0.5)}\right) + \frac{2\gamma\left(\varepsilon - \delta\right)\left\{4\left(\varepsilon - 1\right) + \varepsilon\left[4 + d_{\psi}^{(0.5)}\left(\varepsilon - 1\right)\right]\right\}^{2}}{\varepsilon\left(\varepsilon - 1\right)^{2} \delta a^{f} L\left[4 + d_{\psi}^{(0.5)}\left(\varepsilon - 1\right)\right]}.$$

$$\cdot \frac{\delta^{2}}{4\delta^{2} + 4\varepsilon\left(\varepsilon - 1\right) + \delta^{2} d_{\psi}^{(0.5)}\left(\varepsilon - 1\right) + \sqrt{\left(\varepsilon^{2} - \delta^{2}\right)\left\{\left[4\left(\varepsilon - 1\right)\right]^{2} - \delta^{2}\left[4 + d_{\psi}^{(0.5)}\left(\varepsilon - 1\right)\right]^{2}\right\}}}.$$

The above conditions (1 to 4) can then be re-stated in a simpler way, as follows:

1) If $d_{\psi}^{(0.5)} > d_{\psi,0}$ and $d_{\Theta}^{(0.5)} < \zeta\left(d_{\psi}^{(0.5)}\right)$, $\sigma_{\text{SS}}\left(\phi\right)$ is positive over the whole range $\phi \in \left[0;1\right]$. With Condition 2, this corresponds to case SS–*i* in Proposition 2;
2) If $d_{\psi}^{(0.5)} < d_{\psi,0}$ and $d_{\Theta}^{(0.5)} < \zeta\left(d_{\psi}^{(0.5)}\right)$, $\sigma_{\text{SS}}\left(\phi\right)$ is negative over $\phi \in \left[0;\phi_{b}\right]$ and positive over $\phi \in \left[\phi_{b};1\right]$. With Condition 2, this corresponds to case SS–*ii* in Proposition 2;
3) If $d_{\psi}^{(0.5)} > d_{\psi,0}$ and $d_{\Theta}^{(0.5)} > \zeta\left(d_{\psi}^{(0.5)}\right)$, $\sigma_{\text{SS}}\left(\phi\right)$ is positive over $\phi \in \left[0;\phi_{b}\right]$, and negative over $\phi \in \left[\phi_{b};1\right]$. With Condition 2, this corresponds to case SS–*iii* in Proposition 2;
4) If $d_{\psi}^{(0.5)} < d_{\psi,0}$, and $d_{\Theta}^{(0.5)} > \zeta\left(d_{\psi}^{(0.5)}\right)$:
   a) If $d_{\Theta}^{(0.5)} < \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$, then $\sigma_{\text{SS}}\left(\phi\right)$ is positive over $\phi \in \left[\underline{\phi}_{b};\overline{\phi}_{b}\right]$, and negative over $\phi \in \left[0;1\right] \setminus \left[\underline{\phi}_{b};\overline{\phi}_{b}\right]$. With Condition 2, this corresponds to case SS–*iv* in Proposition 2;
   b) If $d_{\Theta}^{(0.5)} > \zeta_{\Delta}\left(d_{\psi}^{(0.5)}\right)$, then $\sigma_{\text{SS}}\left(\phi\right)$ remains negative over the whole range $\phi \in \left[0;1\right]$. With Condition 2, this corresponds to case SS–*v* in Proposition 2.

This concludes the proof.

A1.3. Partial agglomeration $(0.5 < h < 1)$

Here we provide proof of Proposition 3 in Section *III.1*:

PROOF OF PROPOSITION 3: For a given ϕ satisfying $0 \le \phi \le 1$, we define a function g_{ϕ} such that: $\forall h \in \left[0;1\right], g_{\phi}(h) = \Omega(h,\phi)$. Let us consider case (PA–*i*). This means that the ϕ-value is chosen so that:

- The core-periphery $h = 1$ is a stable equilibrium. According to (18-*b*), this means that: $g_\phi(1) > 0$;
- The symmetric spreading $h = 0.5$ is a stable equilibrium. According to (18-*a*), this means that: $g_\phi(0.5) = 0$ and $g'_\phi(0.5) < 0$.

By continuity of function g_ϕ the last two conditions mean that there exists a value $\bar{h}$ such that $0.5 < \bar{h} < 1$ and $g_\phi\left(\bar{h}\right) < 0$. Conditions $g_\phi\left(\bar{h}\right) < 0$ and $g_\phi(1) > 0$ mean that there exists a value h_0 such that:

$$\begin{Bmatrix} \bar{h} < h_0 < 1 \\ g_\phi\left(h_0\right) = 0 \\ g'_\phi\left(h_0\right) > 0 \end{Bmatrix}.$$

This value h_0 is then an unstable partial agglomeration equilibrium. The proof is similar for case (PA–*ii*).

This concludes the proof.

A2. Long-run partial agglomeration in non-symmetric spatial configurations

A2.1. Core-periphery pattern ($h = 1$)

According to (18-*b*), the full agglomerations $h = 1$ is stable equilibrium under the condition $\Omega(1,\phi) \geq 0$. Using (19) and (20) we derive that this condition is equivalent to:

$$\sigma_{\mathrm{CP}}\left(\phi\right) < \frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon}.$$

CONDITION 3: The core-periphery pattern $h = 1$ is a stable equilibrium for trade barrier $\phi \in \left[0;1\right]$ if: $\frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon} > \sigma_{\mathrm{CP}}\left(\phi\right)$.

The proof of Proposition 4 follows:

PROOF OF PROPOSITION 4: Similarly to condition 1, we can derive the stability conditions of the core-periphery pattern $h = 1$ by substituting $\Theta(1)\psi(1)^{1-\varepsilon}$ with

$\frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon}$. Similarly to Proposition 1, we obtain three possible outcomes for the core-periphery pattern $h = 1$ conditional on the position of $\frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon}$ with respect to $\sigma_{\text{CP}}^{\min}$ and 1: *i)* $h = 1$ is never an equilibrium if $\frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon} < \sigma_{\text{CP}}^{\min}$; *ii)* $h = 1$ is an equilibrium for intermediate trade freeness $\phi \in \left[\underline{\phi}_S^*; \overline{\phi}_S^*\right]$; *iii)* $h = 1$ is an equilibrium for low trade barrier $\phi \in \left[\phi_S^*; 1\right]$ if $\sigma_{\text{CP}}^{\min} < \frac{1}{\nu}\Theta(1)\psi(1)^{1-\varepsilon}$.

A2.2. Core-periphery pattern $(h = 0)$

According to (18-*c*), the case $h = 0$ is a stable equilibrium as long as condition $\Omega(0,\phi) \leq 0$ holds. Using (19) and (20) shows that this condition is equivalent to $\sigma_{\text{CP}}(\phi) < \nu\Theta(1)\psi(1)^{1-\varepsilon}$.

CONDITION 3BIS: The core-periphery pattern $h = 0$ is a stable equilibrium for trade barrier $\phi \in \left[0;1\right]$ if: $\nu\Theta(1)\psi(1)^{1-\varepsilon} > \sigma_{\text{CP}}(\phi)$.

PROOF OF PROPOSITION 5**:** Similarly to Proposition 1, we obtain three possible outcomes for the core-periphery pattern $h = 0$ conditional on the position of $\nu\Theta(1)\psi(1)^{1-\varepsilon}$ with respect to $\sigma_{\text{CP}}^{\min}$ and 1: *i)* $h = 0$ is never an equilibrium if $\nu\Theta(1)\psi(1)^{1-\varepsilon} < \sigma_{\text{CP}}^{\min}$; *ii)* $h = 0$ is an equilibrium for intermediate trade freeness $\phi \in \left[\underline{\phi}_S^{**}; \overline{\phi}_S^{**}\right]$ if $\sigma_{\text{CP}}^{\min} < \nu\Theta(1)\psi(1)^{1-\varepsilon} < 1$; *iii)* $h = 0$ is an equilibrium for a low trade barrier $\phi \in \left[\phi_S^{**}; 1\right]$ if $\nu\Theta(1)\psi(1)^{1-\varepsilon} > 1$.[27]

A2.3. Partial agglomeration $(0.5 < h < 1)$

Here we provide a proof of Proposition 6 in Section *III.2*:

PROOF OF PROPOSITION 6: For a given ϕ satisfying $0 \leq \phi \leq 1$, we define a function g_ϕ such that: $\forall h \in \left[0;1\right], g_\phi(h) = \Omega(h,\phi)$. Let us consider case (PA'$-i$). This means that the ϕ-value is chosen so that:

[27] The threshold point ϕ_S^{**} (with $\underline{\phi}_S^{**}$ and $\overline{\phi}_S^{**}$ indicating its upper and lower value in case of existence of multiple points) is the "sustain point" in the case of full agglomeration $h = 1$ in non-symmetric configurations (see Proposition 1). It is implicitly given by condition $\nu\Theta(1)\psi(1)^{1-\varepsilon} = \sigma_{\text{CP}}(\phi_S^{**})$.

- The core-periphery $h = 1$ is a stable equilibrium. According to (18-b), this means that: $g_\phi(1) > 0$;
- The core-periphery $h = 0$ is a stable equilibrium. According to (18-c), this means that: $g_\phi(0) < 0$.

By continuity of function g_ϕ, this mean that there exists a value h_0 such that:

$$\left\{\begin{matrix} 0 < h_0 < 1 \\ g_\phi\left(h_0\right) = 0 \\ g'_\phi\left(h_0\right) > 0 \end{matrix}\right\}.$$

This value h_0 is an unstable partial agglomeration equilibrium. The proof is similar for case (PA'–*ii*).

This concludes the proof.

A3. Dependence of environmental and market density effects on trade barriers

Here, we demonstrate the following three results regarding the dependence of *market density* and environmental effects on the value of trade barriers ϕ:

A3.1. The market density effect is more intense at low trade barriers

This comes down to demonstrating that $\sigma_{\mathrm{SS}}^{(\psi)}\left(\phi\right)$ in *III.C* and (A-6) is increasing in ϕ. The function $\sigma_{\mathrm{SS}}^{(\psi)}\left(\phi\right)$ is a second-order polynomial in ϕ. Its dominant term $-\dfrac{1}{2}\delta\left(\varepsilon+\delta\right)$ is negative, so that $\sigma_{\mathrm{SS}}^{(\psi)}\left(\phi\right)$ is a concave function. It reaches a minimum at $\phi = \phi_m^{(\psi)}$, implicitly defined by $\dfrac{\partial\sigma_{\mathrm{SS}}^{(\psi)}}{\partial\phi}\left(\phi_m^{(\psi)}\right) = 0$. Function $\sigma_{\mathrm{SS}}^{(\psi)}\left(\phi\right)$ is increasing for $\phi < \phi_m^{(\psi)}$, while decreasing for $\phi > \phi_m^{(\psi)}$. From equation (A-7), it follows that $\phi_m^{(\psi)} = \dfrac{4\varepsilon\left(\varepsilon-1\right)+2\delta^2}{2\delta\left(\varepsilon+\delta\right)}$. With the "no black hole" condition $\varepsilon - 1 > \delta$, we have $\dfrac{4\varepsilon\left(\varepsilon-1\right)+2\delta^2}{2\delta\left(\varepsilon+\delta\right)} > \dfrac{\varepsilon}{\varepsilon+\delta} + 1$, so that $\phi_m^{(\psi)} > 1$. This means in particular that $\sigma_{\mathrm{SS}}^{(\psi)}\left(\phi\right)$ is increasing over $\phi \in \left[0;1\right]$. This demonstrates the result.

A3.2. The environmental effect is more intense at low trade barriers

This comes down to demonstrating that $\sigma_{SS}^{(\Theta)}\left(\phi\right)$ in *III.C* and (A-6) is increasing in ϕ. The function $\sigma_{SS}^{(\Theta)}\left(\phi\right)$ is linear in ϕ, with a positive multiplicative term $\frac{\delta\varepsilon a^f L\left(\varepsilon-1\right)}{\gamma\left(\varepsilon-\delta\right)}\left(2+d_{\psi}^{(0.5)}\frac{\varepsilon-1}{2}\right)$, so that $\sigma_{SS}^{(\Theta)}\left(\phi\right)$ is uniformly increasing. This demonstrates the result.

A3.3. The environmental effect is stronger than the market density effect at low trade barriers

This comes down to showing that the ratio $\frac{\sigma_{SS}^{(\Theta)}\left(\phi\right)}{\sigma_{SS}^{(\psi)}\left(\phi\right)}$ is increasing in ϕ. From equation (A-7) it follows that the ratio $\frac{\sigma_{SS}^{(\Theta)}\left(\phi\right)}{\sigma_{SS}^{(\psi)}\left(\phi\right)}=\frac{\frac{\delta\varepsilon a^f L\left(\varepsilon-1\right)}{\gamma\left(\varepsilon-\delta\right)}\left(4+d_{\psi}^{(0.5)}\left(\varepsilon-1\right)\right)}{\left[4\varepsilon\left(\varepsilon-1\right)+2\delta^2\right]+\frac{1}{\phi}\delta\left(\varepsilon-\delta\right)-\delta\phi\left(\varepsilon+\delta\right)}$. Since the denominator is a decreasing function in ϕ, $\frac{\sigma_{SS}^{(\Theta)}\left(\phi\right)}{\sigma_{SS}^{(\psi)}\left(\phi\right)}$ is increasing in ϕ.

A4. Values of model parameters and exogenous variables

A4.1. Parameters and exogenous variables defining the economy

In line with the literature (Grazi *et al.*, 2007), the exogenous variable total unskilled labor availability L is set equal to 5. We normalize the global skilled population to 1, i.e. $H=H_1+H_2=1$. Whenever possible, the values of the economic parameters have been taken from the literature on spatial and trade economics (e.g., Fujita *et al.*, 1999; Fujita and Thisse, 2002; Bernard *et al.*, 2003). The share of income spent on manufactured goods in eq. (1) is set equal $\delta=0.4$. The elasticity of substitution in eq. (1) is $\varepsilon=3$. Finally we assume a one-to-one production structure in the energy sector (one unskilled worker produces one unit of energy), which comes down to setting the labor requirement parameter in (6) $\gamma=1$.

A4.2. Parameters defining local pollution E_j^L

Concerning the local pollution parameters, the parameter a^L in eq. (13) is normalized to 1, as a definition of the unit of measure of pollution-externality flow arising from manufacturing production.

A4.3. The market form parameter β_j

The parameter β_j captures the exogenous spatial characteristics of region *j* in terms of the degree of (telecommunication and electricity) infrastructure development characterizing the economy's configuration (see Section *II.1*). Regional spatial structure alters the energy intensity of production activities that are located in *j*. Two types of regional spatial structure are considered: one is characterized by an 'urbanized' region, with a high degree of infrastructure development (as captured by a low value of β_j); another by a less urbanized, 'undeveloped' region, with little land development (high value of β_j). When considering configurations with *symmetric* spatial structure, the β_j parameters enter the indirect utility differential only through the multiplicative term $\frac{\Gamma'}{\beta_j^{\delta}}$ (see eq. (19) and eq. (20) in the case $\beta_1 = \beta_2$). This term is constant and strictly positive and, hence, a change in the β-value does not modify the stability conditions in (19).

When *asymmetric* configurations are considered, the β-parameters enter the indirect utility differential through the ratio $\left(\beta_2/\beta_1\right)^{1-\varepsilon}$ (see eq. (19) and eq. (20) in the case $\beta_1 \neq \beta_2$). In this case, long-run development patterns driven by the utility differential depend entirely on the relative numerical values of the parameters. Without loss of generality, we set $\beta_1 = 1$ and let the numerical value of the ratio β_2/β_1 be calibrated over some alternative trend of energy-intensity of the economy between two comparable regions, such as, e.g. the USA and Europe. For the year 2006, official data from the EIA give an energy intensity of economic activity (amount of energy used per unit of value added) of 8840 Btu/$ in the USA and 6536 Btu/$ in Europe.[28] The β-parameters capture these differences in energy intensity, so

[28] See http://www.eia.doe.gov/emeu/international/energyconsumption.html.

that we obtain $\frac{\beta_2}{\beta_1} = \frac{8840}{6536} \approx 1.35$. With $\beta_1 = 1$, this leads $\beta_2 = 1.35$ and $\nu = \left(\beta_2/\beta_1\right)^{1-\varepsilon} \approx \left(1.35\right)^{1-\varepsilon} = 0.55$.

Table A1: Values of the agglomeration parameters in the configurations

Spatial Configuration	β_1 *(Region 1)*	β_2 *(Region 2)*
A (both regions with undeveloped land)	1.35	1.35
B (both regions with urbanized land)	1	1
C (one region urbanized, other undeveloped)	1	1.35

A5. Functional Specifications

A5.1. The market density effect function $\overline{\psi}\left(n_j\right)$

Function $\overline{\psi}\left(n_j\right)$ captures the decrease of energy-related production costs resulting from agglomeration of firms in the *j* region. By assumption, this function is decreasing in n_j and satisfies condition: $\overline{\psi}\left(0\right) = 1$. Given the relation between the number of active firms in region *j* and the amount of skilled workers regionally employed [see eq.(9)] and defining $h = \frac{H_1}{H}$ as the share of the regional population, the *market density* effect $\overline{\psi}\left(n_j\right)$ can be re-written as a function of *h*: $\psi\left(h\right)$. We choose to adopt an exponential mathematical form: $\psi\left(h\right) = e^{-\mu_\psi h}$ where μ_ψ is a positive constant. Such a function satisfies $\psi''\left(h\right) > 0$ so that the *market density* effect features decreasing returns to agglomeration: production costs are less reduced by a marginal increase in the degree of agglomeration if production is already intensely agglomerated. This exponential mathematical form is convenient since it leads to simple analytical expressions for $d_\psi^{(0.5)}$ providing a straightforward interpretation of parameter μ_ψ. Indeed, since $d_\psi^{(0.5)} = 2\mu_\psi$ it follows that μ_ψ measures directly the intensity of the *market density* effect, ψ. We choose numerical values of μ_ψ that allow for considering non-trivial cases in which the effect of agglomeration is strong enough to affect agents' location choices. This comes down to assuming a strong *market density* effect, which corresponds to the analytical condition $d_\psi^{(0.5)} > d_{\psi,0}$ (see section *III.1*), with $d_\psi^{(0.5)} = 2\mu_\psi$. This can be rewritten as $\mu_\psi > \frac{d_{\psi,0}}{2}$. Taking

$\delta = 0.4$ and $\varepsilon = 3$, and recalling $d_{\psi,0} = \dfrac{4\left(\varepsilon - 1 - \delta\right)}{\delta(\varepsilon - 1)}$ gives $d_{\psi,0} = 8$ and hence $\mu_{\psi} > 4$. For the ease of computation, we take $\mu_{\psi} = 5$. We are then able to study cases where positive *market density* effects play an important role. Such cases have never been investigated in the literature because of the inherent limitations of existing frameworks in which the *market density* effect is not measurable.

A5.2. The environmental-externality function $\Theta\left(E_j^L\right)$

It captures the decrease of utility due to the effect of negative local environmental externalities. We posit this function to be decreasing and satisfy condition $\Theta\left(0\right) = 1$. We set $\Theta\left(E_j^L\right) = 2 - e^{\mu_{\Theta} E_j^L}$ where μ_{Θ} is a positive constant capturing the intensity of the negative environmental effect. This function satisfies the condition: $\Theta''\left(E_j^L\right) = -\left(\mu_{\Theta}\right)^2 e^{\mu_{\Theta} E_j^L} < 0$, to capture the non-linear response of environmental damage to pollution.

We choose numerical values of μ_{Θ} that allow consideration of non-trivial cases in which the environmental effect is not fully dominating the agglomeration and trade effects, as this case is of little relevance to a thorough analysis of sustainability, in which agglomeration and trade do matter. Recalling that $d_{\Theta}^{(0.5)} > \zeta\left(d_{\psi}^{(0.5)}\right)$ corresponds to a 'strong' environmental effect, whereas $d_{\Theta}^{(0.5)} < \zeta\left(d_{\psi}^{(0.5)}\right)$ captures a 'weak' environmental effect (see section *II.1*), we retain the case $d_{\Theta}^{(0.5)} = \zeta\left(d_{\psi}^{(0.5)}\right)$, which corresponds to the environmental effect taking a moderate, mean intensity on utility. This analytical condition leads to setting a numerical value of $\mu_{\Theta} = 0.45$.

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