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The Economics of Spatial Sustainability:

General Theory and Application to Climate Change

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The Economics of Spatial Sustainability: General Theory and Application to Climate Change

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Summary

This paper formalizes the notion of 'spatial sustainability' of an economy in the presence of local and global environmental externalities. An extension is offered here of a new economic geography (NEG) model with environment, which relieves the standard focus on local and flow pollutants by adding a dynamic analysis of global cumulative pollution, like carbon dioxide emissions causing climate change. The model is used to assess the role of alternative spatial planning and trade policies to achieve long-term emissions reduction targets, which are consistent with sustainability. Our exercise can be especially insightful in the context of climate change, where extra emission reduction options are urgently needed to reach very ambitious emission targets.

Keywords: General equilibrium modeling, Global (pollution and GHG) emissions dynamics, New economic geography, Spatial planning and policy, Trade policy.

JEL Classification: F12, F18, Q56, Q58, R12, R13.

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I. Introduction

Translating the notion of global sustainable development into concrete principles and actions at local, regional, and national levels has turned out to be difficult (OECD, 2007; 2010). One reason is that there is no agreed framework for studying the spatial dimension of sustainable development. The relation between international trade, location and environment has received considerable attention, but most of the literature ignores dynamic issues related to sustainability (Copeland and Taylor, 2004).

This paper presents a theoretical framework for analyzing the impact of spatial structure of the economy on its long-run sustainability. We introduce the notion of "spatial sustainability" to denote that spatial configurations and economic dynamics are consistent with environmental constraints, such as the capacity to assimilate pollution (Pezzey and Toman, 2005). We focus on global environmental issues, notably emissions of greenhouse gasses (GHG) due to energy use, which give rise to climate change (IPCC, 2007*a*).

In order to formalize spatial sustainability in a way that is consistent with economic theory we use an existing general equilibrium model recently developed by Grazi *et al.* (2016) (GVW, henceforth) which is based on the new economic geography (NEG) (Krugman, 1991). The GVW model integrates five elements that influence the spatial structure of the regional economy in the long run, namely: positive agglomeration externalities; negative environmental externalities; the so-called "market-density" external effect, which captures the energy intensity of production due to the spatial distribution of economic activity; interregional trade; and factor mobility (population and firm migration). The GVW model is here extended with global stock pollution and related dynamics, allowing for an analysis of the long-run (un)sustainability performance of the economy and its spatial configuration. The resulting model will be used to assess the capacity of alternative spatial planning and trade policies to achieve long-term (spatial) sustainability. Our extension to include global and stock pollutants and environmental dynamics enables connecting the NEG literature with the existing literatures on trade and environment. The latter uses a distinct theoretical framework that focuses on the role of trade costs on transboundary pollution and the environment's "regenerative capacity" (Copeland and Taylor, 1994; 1995; 1999).

Following Krugman's seminal work (1991), a considerable literature on the NEG emerged addressing the mechanisms through which economies develop in space. Yet few studies that employ the NEG framework have addressed environmental issues, and none has explicitly considered the policy connection between spatial structure, environmental dynamics and sustainability.[1] Here we provide such a comprehensive framework integrating space, trade, environmental dynamics and long-term emissions reduction. This leads to an improved study of spatial and trade effects in environmental regulation, which can be especially helpful in the context of climate change, where extra emission reduction options are urgently needed to meet very ambitious climate policy goals.

The remainder of this paper is organized as follows. Section II summarizes the basic GVW model by Grazi *et al.* (2016). Section III extends the model with pollution dynamics to derive long-run spatial equilibria that satisfy environmental sustainability. Section IV provides a numerical application of the extended model to evaluate and rank three different spatial configurations of the economy in terms of sustainability performance. Section V concludes.

II. The Basic Model

Here the rationale of the modeling approach is summarized along with key technical features that we consider relevant to the comprehension of the model extension presented in Section III. We use the same notation as in the original GVW model (Grazi *et al.*, 2016).

II.1. The spatial economy

The global economy consists 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 varieties i of a horizontally-differentiated final good using skilled labor H and energy ξ as input factors. A third sector is an aggregated sector, which produces a homogeneous traditional final good using only unskilled labor L. As opposed to unskilled labor, skilled labor is assumed to be mobile across regions. The manufacturing sector uses energy as a variable input of production. Pollution is emitted as a by-product of energy use. Finally, the cost of interregional trade of the manufactured good follows Samuelson's (1952) iceberg structure. In line with the standard NEG literature, trade costs are assumed to be zero for both inter- and intra-regional shipment of the traditional good.

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[1] See Grazi *et al.* (2016) for a comprehensive synthesis of the literature on NEG and environment.

II.2. Households

Households maximize utility by consuming a traditional commodity, Q, and an aggregate manufactured good, M. They suffer from external environmental effects, captured by a multiplicative term in utility, $\Theta\left(E_j^L\right)$, where E_j^L denotes local flow pollution.

$$U_j = M_j^{\delta} Q_j^{1-\delta} \Theta\left(E_j^L\right), \quad j = (1,2); \Theta\left(E_j^L\right) \leq 1 \tag{1}$$

Domestic consumption of the traded manufactured good c_{kj} results from standard utility maximization:

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

Here p_{kj} is the shipping price of a good produced in k and consumed in j, ε is the standard elasticity of substitution in the CES sub-utility function M à la Dixit and Stiglitz (1977), Υ_j is the domestically available income, and $I_j = \left[n_j p_j^{1-\varepsilon} + n_k p_{kj}^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}}$ is Dixit-Stiglitz's (1977) price index of the manufactured good in j.

II.3. Firms

A typical j-firm producing a quantity x_j of the manufactured good incurs total costs χ_j which consist of fixed costs in skilled labor, αw_j, and variable costs in unitary energy requirements, $p^{\xi}\xi_j$:

$$\chi_j = \alpha w_j + p^{\xi} \xi_j x_j. \tag{3}$$

Here α is a constant, w_j is the wage rate of skilled workers, ξ_j is the intermediate energy good for production, and p^{ξ} its price independent of the region j.

The regional production setting in (3) is affected by spatial spillover effects due to proximity of economic activities in space, which reduce the energy cost component ξ_j of producing varieties in the regional manufacturing sector. In particular, two spatial determinants of the energy intensity of domestic production are identified, the "market form" exogenous effect, β_j, and the "market density" endogenous effect, $\bar{\psi}\left(n_j\right)$, as from original definition (Grazi *et al.*, 2016):

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

The "market form" parameter, β_j, denotes the impact of a given regional spatial form and extension (infrastructure) on the energy intensity of manufacturing production. It captures (is inversely related to) the degree of 'urbanization' of a given spatial economy, or the spatial concentration of domestic (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. In line with the GVW model, two possible spatial forms for each region are considered, namely: intense land and infrastructure development in support of economic activity (i.e. urbanized space); and a less intensive use of space (i.e. undeveloped land). This gives rise to three spatial configurations of the global economy:[2] an asymmetric configuration (A) reflects an (urban + undeveloped) regional spatial setting; a symmetric configuration (B) depicts an (urban + urban) type of spatial organization; and a symmetric configuration (C) represents an (undeveloped + undeveloped) spatial structure. For each spatial configuration $\lambda \in \left\{\mathrm{A,B,C}\right\}$ this paper analytically derives the condition under which the long-run equilibrium properties provided in the GVW model by Grazi *et al.* (2016) satisfy environmental sustainability (see Section III further below). It further evaluates and ranks each configuration $\lambda \in \left\{\mathrm{A,B,C}\right\}$ in terms of its sustainability performance (see Section IV).

The "market density" effect, captured by $\bar{\psi}\left(n_j\right)$, is an endogenous spillover effect at the industry level and represents the impact of market density, a function of the number of firms in the regional market, on the energy requirement of production. More precisely, the multiplicative term $\bar{\psi}\left(n_j\right)$ captures the impact of the market density on technological spillovers.[3] Following GVW analysis, $\bar{\psi}\left(0\right) = 1$ indicates no positive effect

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[2] 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.

[3] The 'market-density' external effect is the main contribution of the GVW model to the economic literature on space and environment. It 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).

of agglomeration on production costs in the absence of firms, whereas $\bar{\psi}'\left(n_j\right) < 0$ means 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:

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

The traditional good and the energy commodity are produced using unskilled labor as a linear input. We take the wage of unskilled workers as the *numéraire*.[4] As a result of constant unitary labor requirement per unit of output, γ, marginal cost pricing in the energy sector gives:

$$p^{\xi} = \gamma. \tag{6}$$

Finally, the domestic production of the homogeneous traditional good is:

$$Q_j = L / 2 - \gamma \xi_j n_j x_j. \tag{7}$$

Note that 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.4. 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.

II.4.1. Income

$$\Upsilon_j = w_j H_j + L / 2. \tag{8}$$

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.

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[4] See Grazi *et al.* (2016) for a more detailed explanation.

II.4.2. Market size

$$n_j = \frac{H_j}{\alpha}, \tag{9}$$

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.

II.4.3. Wage

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

We recall that parameters α and γ define the proportionality between the labor requirement and final output in the manufacturing and energy sectors, respectively (see equations (3) and (6)

II.4.4. Production size

$$x_j = \delta \left[\frac{\gamma \xi_j \varepsilon}{\varepsilon - 1} \right]^{-\varepsilon} \left(\frac{\Upsilon_j}{I_j^{1-\varepsilon}} + \frac{\phi \Upsilon_k}{I_k^{1-\varepsilon}} \right). \tag{11}$$

Here I_j is the regional price index and $\phi = T^{1-\varepsilon}$ is the standard NEG parameter measuring the freeness of interregional trade. We recall that $\phi = 0$ represents maximal barriers to interregional trade (or autarky), while $\phi = 1$ reflects free trade across regions.[5]

II.5. Local pollution externalities

In line with the (still relatively small) literature on NEG with environmental applications, the GVW model posits that the environmental externality (pollution) is

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[5] 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.

local and only generated by manufacturing.[6] Moreover, it assumes proportionality between total energy use, $\xi_j n_j x_j$, and emissions of local pollutants in region *j*, E_j^L:

$$E_j^L = a^L \xi_j n_j x_j. \tag{12}$$

Going back to the definition of individual utility in (1), $\Theta(0) = 1$ indicates 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.[7]

II.6. The long-run model and the dynamics of migration

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:

$$\Omega(h,\phi) = \Gamma\left[\frac{w_1(h,\phi)}{I_1(h,\phi)^\delta}\Theta(h,\phi) - \frac{w_2(h,\phi)}{I_2(h,\phi)^\delta}\Theta(1-h,\phi)\right]. \tag{13}$$

Given $h \in [0;1]$, the equation describing the dynamics of factor mobility can be expressed as follows:[8]

$$\frac{dh}{dt} = \begin{cases} \Omega(h,\phi), & \text{if } 0 < h < 1 \\ \max(0,\Omega(h,\phi)), & \text{if } h = 0 \\ \min(0,\Omega(h,\phi)), & \text{if } h = 1 \end{cases}. \tag{14}$$

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

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[6] Section III extends the GVW's (2016) model to relax this assumption and formally consider global environmental externalities that arise from interregional trade/transport as well. This is functional to the aim of addressing sustainability.

[7] Note that given equation (9) and dependence of local emissions, E_j^L, on the size of the regional market, n_j, in (12), 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, $h = H_1/H : \Theta(h)$. This relation will be adopted in the remainder of the long-run analysis.

[8] 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.

$$\frac{dh}{dt} = 0. \tag{15}$$

For stability of the long-run equilibrium one of the three following conditions must hold:

$$a)\begin{cases} 0 < h < 1 \\ \Omega(h,\phi) = 0, \dfrac{\partial \Omega}{\partial h}(h,\phi) < 0 \end{cases}; \quad b)\begin{cases} h = 1 \\ \Omega(h,\phi) \geq 0 \end{cases}; \quad c)\begin{cases} h = 0 \\ \Omega(h,\phi) \leq 0 \end{cases}. \tag{16}$$

III. Extending the Model with Sustainability

In this section we extend the basic GVW new economic geography (NEG) model by Grazi *et al.* (2016), to relieve the standard focus of NEG analyses on local and flow pollutants and model the effects of global emission externalities and pollution stock on utility. This is necessary to formalize the notion of spatial sustainability and further deal with topical global environmental problems like climate change. Addressing environmental sustainability in the context of climate change comes down to setting a hard constraint on the atmospheric concentration of greenhouse gas (GHG) emissions. We analyze the long-term interplay between pollution dynamics, spatial location of economic activities and associated energy requirement and trade patterns to derive the consequences of setting constraints over GHG emissions on the stability of long-term equilibria. In so doing we make a connection with the literature that goes under the name of 'trade and environment', and which focuses on the role of trade costs on pollution (Copeland and Taylor, 1994; 1995).

III.1. Global pollution emissions and trade

In the strand of literature that followed Copeland and Taylor (1994; 1995), the relation between spatial concentration and environmental externalities is mainly driven by the negative effect of pollution on utility and productivity (Copeland and Taylor, 1999; Benarroch and Thille, 2001; Unteroberdoerster, 2001). We engage with these analyses by considering *i*) the role of the spatial dimension of the economy on pollution through the impact of the type of spatial structure (urbanized versus undeveloped land use) on energy requirements for domestic manufacturing production, as captured by parameter β in eq. (4); *ii*) the positive impact of agglomeration on productivity through a decrease of unitary energy requirements for production in more agglomerated production patterns as captured by variable $\bar{\psi}\left(n_j\right)$ in (4).

For the purpose of analyzing environmental sustainability in the context of the climate change debate, we represent greenhouse gas (GHG) emissions as global emission externalities E^G affecting equally both regions, regardless of their source. We consider two sources of GHG emissions: intermediate consumption of energy for manufacturing production $\left(\xi_j n_j x_j + \xi_k n_k x_k\right)$ and transboundary emissions as generated by international trade. These latter are assumed to be proportional to the volume of trade that is necessary to satisfy the domestic demand for imported goods $\left(Tc_{jk} + Tc_{kj}\right)$. Introducing a^G and b^G as the intensity of global pollution generated by intermediate energy requirements for the manufacturing production and interregional trade of final goods, respectively, global emissions E^G are given by:

$$E^G = a^G\left(\xi_j n_j x_j + \xi_k n_k x_k\right) + b^G\left(Tc_{jk} n_j + Tc_{kj} n_k\right). \tag{17}$$

The amount of long-term global GHG emissions in (15) depends on trade freeness through the interplay between three effects. First, the iceberg structure for transport costs implies that lower trade barrier brings about a decrease of emissions per unit of good shipped. Second, for a given spatial distribution of the economic activities, a trade barrier affects the quantity of good actually shipped from one region to another, since freer trade fosters a higher demand for imported good in both regions. This ultimately acts in the direction of increasing trade-related emissions. Third, trade freeness affects the long-term location of economic activities (see Figures I and II in the GVW analysis by Grazi *et al.*, 2016), which ultimately determines both the intensity of trade as a consequence of the uneven distribution of production and consumption locations,[9] and the level of global economic activity because of the effects of agglomeration on regional and aggregate production.

Note that in our model energy use for production is responsible for both local pollution as in (12) and global emission as in (17). Despite their common source (the energy sector), these pollutants are different in nature and have distinct consequences on the economic setting. In particular, global pollution emissions have identical effect in both regions and hence play no role in individuals' migration decisions.[10] The impact of global externalities on the economic setting is one of stock effect and occurs through accumulation of emissions over time. This calls for a specific representation of their dynamics.

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[9] For example, full agglomeration in one region creates the need to export manufacturing goods for unskilled workers in the other region.

[10] Note in fact that global pollution does not enter the household's utility in (1).

III.2. Dynamics of global externalities and emission mitigation scenarios

Here we introduce the notion of "environmental capital" K, which can be interpreted as an inverse measure of the damages caused by climate change. This means that a high capital K is associated with a stable climate, as the one of the pre-industrial economy, when stock of GHGs was relatively low.

For the sake of comparability with the literature on trade and the environment following Copeland and Taylor (1999), we describe the dynamics of the environmental capital K as resulting from the negative effect of emissions E^G and from the climate's "regenerative capacity", $F(K)$:

$$\frac{dK}{dt} = F(K) - E^G. \tag{18}$$

In the literature following Copeland and Taylor (1999), the function $F(K)$ is traditionally assumed to be a linear function of the difference with a "natural level" $\bar{K}$ at a "recovery rate" g: $F(K) = g\left(\bar{K} - K\right)$ (e.g., Copeland and Taylor, 1999). Such a formulation is suitable to describe small variations of the environmental quality. However, it completely neglects the possibility of breakthroughs in the dynamics of environmental quality.[11]

When dealing with sustainability in the context of a global environmental externality like climate change, much scientific consensus exists about the risk of drastic changes in view of non-linear, catastrophic mechanisms that affect "regenerative capacity" $F(K)$. One can think here of natural carbon sequestration by oceans and vegetation for a high level of GHG concentration (i.e. a low level of environmental capital). We represent the occurrence of these irreversible mechanisms by introducing a drop in the environment's "regenerative capacity" $F(K)$ at low levels of environmental capital stock. To keep the analysis simple we distinguish between two regimes of environment's "regenerative capacity" and assume that: *i*) at medium and high levels of environmental stock (medium and low levels of GHG concentration), the "regenerative capacity" of the environment is a constant process A (Gradus and Smulders, 1993); Keeler *et al.*, 1971; van der Ploeg and Withagen, 1991), which we call the 'emission assimilation potential' and that represents the maximum of the natural recovery rate of the environment). In the case of climate change that we treat here, the emission assimilation potential can be interpreted as the (natural) biological and ocean

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[11] In fact since dK/dt is still positive at $K = 0$, there is no minimum viable level of environmental capital stock

carbon sequestration ; *ii*) at a low level of the environmental stock (high level of GHG emission concentration), the "regenerative capacity" of the environment drops to zero. This leads to:

$$F(K) = \begin{Bmatrix} A & if\ K \geq \bar{K} \\ 0 & if\ K < \bar{K} \end{Bmatrix}. \tag{19}$$

Here, $\bar{K}$ is a threshold below which the regenerative capacity drops to zero. The functional specification for the environment's "regenerative capacity" ensures that $\frac{dK}{dt} < 0$ at $K = 0$, or that falling below a certain level of environmental quality may turn out irreversible. This means that sustainability of the economy is consistent with non-decreasing trend of the climate quality in the long-term, as follows: $\frac{dK}{dt} \geq 0$. According to (18) and (19), this leads to:

$$E^G\left(h, \phi\right) < A. \tag{20}$$

In the light of applying the modeling analysis to the context of climate change, parameter A can be reinterpreted as the maximum amount of GHG emissions tolerated in the long-term to avoid catastrophic damages from climate change, implying an "acceptable" temperature increase. Table 1 from IPCC (2007*b*) establishes such a correspondence between long-term emissions (in 2050) and ranges of temperature increase (see fourth and sixth columns). For example, the normative limit +2°C corresponds to category I of mitigation scenarios of IPCC (2007*b*) implying an 85% reduction of carbon emissions by 2050, the equivalent of relatively low A values (see Table 1). On the contrary, policy targets allowing for a +4°C increase in average temperature would imply emissions reduction of only 5%, corresponding with high A values in (20). Therefore, A captures the stringency of environmental policy: a lower (higher) A means a more (less) ambitious emissions mitigation target.

Table 1: GHG emissions mitigation scenarios and corresponding temperature increase.

Category	*Radiative Forcing*	*CO$_2$ Concentration*	*CO$_2$-eq Concentration*	*Global mean temperature increase above pre-industrial**	*Peaking year for CO$_2$ emissions*	*Change in global CO$_2$ emissions in 2050*	*Number of assessed scenarios*
	(W/m^2)	*(ppm)*	*(ppm)*	*(°C)*		*(%, 2000 emissions)*	
I	2.5-3.0	350-400	445-490	2.0-2.4	2000-2015	-85 to -50	6
II	3.0-3.5	400-450	490-535	2.4-2.8	2000-2020	-60 to -30	18
III	3.5-4.0	440-485	535-590	2.8-3.2	2010-2030	-30 to +5	21
IV	4.0-5.0	485-570	590-710	3.2-4.0	2020-2060	+10 to	118
V	5.0-6.0	570-660	710-855	4.0-4.9	2050-2080	+25 to	9
VI	6.0-7.5	660-790	855-1130	4.9-6.1	2060-2090	+90 to	5
						Total	*177*

Source: IPCC, 2007b

*Note: Figures reported here refer to equilibrium values obtained using "best-estimate" climate sensitivity

III.3. Formalizing spatial sustainability

Here, we address the spatial or geographical nature of sustainability, in the sense defined in the previous subsection. This means investigating the conditions under which the long-run equilibrium properties of the two-region economy analyzed in Section III of the GVW model by Grazi *et al.* (2016) are compatible with condition (20). A sustainable long-run equilibrium exists if one of the three following sets of conditions is satisfied:

$$(21)\ a)\begin{cases} 0 < h < 1 \\ \Omega(h,\phi) = 0, \dfrac{\partial \Omega}{\partial h}(h,\phi) < 0; \\ E^G(h,\phi) \le A \end{cases} \quad b)\begin{cases} h = 1 \\ \Omega(h,\phi) \ge 0 \\ E^G(h,\phi) \le A \end{cases} ; \quad c)\begin{cases} h = 0 \\ \Omega(h,\phi) \le 0 \\ E^G(h,\phi) \le A \end{cases} .$$

If condition *a)* in (21) holds, the distribution of population with a share h of workers in region 1 (and a share $(1-h)$ in region 2) is a sustainable long-run equilibrium for the spatial configuration considered. If condition *b)* (condition *c)*) holds, a full agglomeration of skilled workers in region 1 (region 2) is the sustainable long-run equilibrium. Finally, if none of the three conditions is satisfied, the spatial configuration is always unsustainable, that is, for all possible trade barriers and spatial distributions of the population.

For a given spatial configuration $\lambda \in \left\{\mathrm{A},\mathrm{B},\mathrm{C}\right\}$ (see description in *II.C*), we define $E_{\lambda}^{G,\min}$ and $E_{\lambda}^{G,\max}$ to denote the minimum and maximum long-run levels of polluting emissions over all ranges of trade barrier. Three cases can occur:

CASE 1: For high configurations in terms of emission characterized by the condition $E_{\lambda}^{G,\min} > A$, the level of long-run pollution is always larger than the pollution assimilation potential A, whatever the trade barrier ϕ. This means that the spatial configuration considered is always unsustainable.

For any other type of configuration, there exists a range of ϕ-values that satisfies (20). We define $\phi_{\lambda}^{*}(A)$ as the highest of these values (lowest trade barrier), meaning the minimum constraint on the economy in terms of barriers to trade to ensure a sustainable development of a spatial configuration λ.[12] Setting a constraint on long-term emissions, as imposed by spatial sustainability in (20) results from the interplay between minimum trade barriers, $\phi_{\lambda}^{*}(A)$, the λ-specific global pollution, and the threshold on long-term emissions A, as follows:

$$E_{\lambda}^{G}\left(h,\phi_{\lambda}^{*}(A)\right) = \min\left(A, E_{\lambda}^{G,\max}\right). \tag{22}$$

CASE 2: For intermediate configurations in terms of emission characterized by the condition $E_{\lambda}^{G,\min} < A < E_{\lambda}^{G,\max}$, the relation in (20) becomes $E_{\lambda}^{G}\left(h,\phi_{\lambda}^{*}(A)\right) = A$. The corresponding solution in $\phi_{\lambda}^{*}(A)$ is such that: $0 < \phi_{\lambda}^{*}(A) < 1$. In this case, the configuration considered satisfies (does not satisfy) the sustainability conditions on emissions if trade barriers are high (low) enough: $\phi < \phi_{\lambda}^{*}(A)$ ($\phi > \phi_{\lambda}^{*}(A)$).

CASE 3: For low configurations in terms of emission characterized by the condition $E_{\lambda}^{G,\max} < A$, the configuration considered satisfies the sustainability conditions on emissions whatever the value of trade barrier. In particular, the configuration remains sustainable even if free trade is assumed as expressed by $\phi_{\lambda}^{*}(A) = 1$.

We are now able to assess the sustainability characteristics of any spatial configuration λ by considering the minimum value of the trade barrier $\phi_{\lambda}^{*}(A)$ that ensures that the stock of environmental capital increases in the long term.

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[12] Intuitively, condition $\phi_{\lambda}^{*}(A) = 0$ expresses the unsustainability of the above Case 1.

IV. Numerical Application

Here we provide a numerical application of the extended model to evaluate and rank the three different spatial configurations of the economy in terms of their sustainability performance in the context of given global (pollution or greenhouse gas, GHG) emissions mitigation targets. By substituting (2), (9) and (11) into (17), and considering baseline values for the model parameters and exogenous variables (see Appendix A.1), we compute the threshold values for global emissions $E_{\lambda}^{G,\min}$ and $E_{\lambda}^{G,\max}$ for each of the three configurations $\lambda \in \left\{\mathrm{A},\mathrm{B},\mathrm{C}\right\}$ (Table 2).

Table 2: Threshold values for emissions in the three spatial configurations

Spatial configuration, λ	*Emission threshold values, $E_{\lambda}^{G,\min;\max}$*	
	$E_{\lambda}^{G,\min}$	$E_{\lambda}^{G,\max}$
A (both regions with undeveloped land)	1.54	1.67
B (both regions with urbanized land)	1.54	1.72
C (one region urbanized, other undeveloped)	1.54	1.70

We then compare the performance of the three spatial configurations in terms of sustainability of the final long-run spatial equilibrium by investigating the variation of the minimum trade barrier for sustainability $\phi_{\lambda}^{*}(A)$ across the configurations for a given level of the pollution/GHG assimilation potential A.

We limit the analysis to the range of A-values that are not associated with trivial outcomes, that is, we exclude those for which the three spatial configurations under consideration are either never or always sustainable. For this purpose, we define $A^{\min}$ and $A^{\max}$ as the minimum and maximum values of $E_{\lambda}^{G,\min}$ and $E_{\lambda}^{G,\max}$ across all spatial configurations, respectively. In other words, $A^{\min} = \min_{\lambda \in \left\{A,B,C\right\}} E_{\lambda}^{G,\min}$ and $A^{\max} = \max_{\lambda \in \left\{A,B,C\right\}} E_{\lambda}^{G,\max}$. For the numerical data summarized in Table 3, $A^{\min} = 1.54$ and $A^{\max} = 1.72$. In order to perform a non-trivial analysis of the sustainability of the configurations, we do not consider the cases where $A < A^{\min}$ with the three configurations in Case 1, nor $A > A^{\max}$ with all configurations in Case 3. In other words, we only consider values of A satisfying $A^{\min} \leq A \leq A^{\max}$ and are interested in the numerical values of the lowest trade barrier that satisfies the sustainability condition in (20) for all the three spatial configurations $\lambda \in \{A, B, C\}$. Figure I summarizes graphically the results.

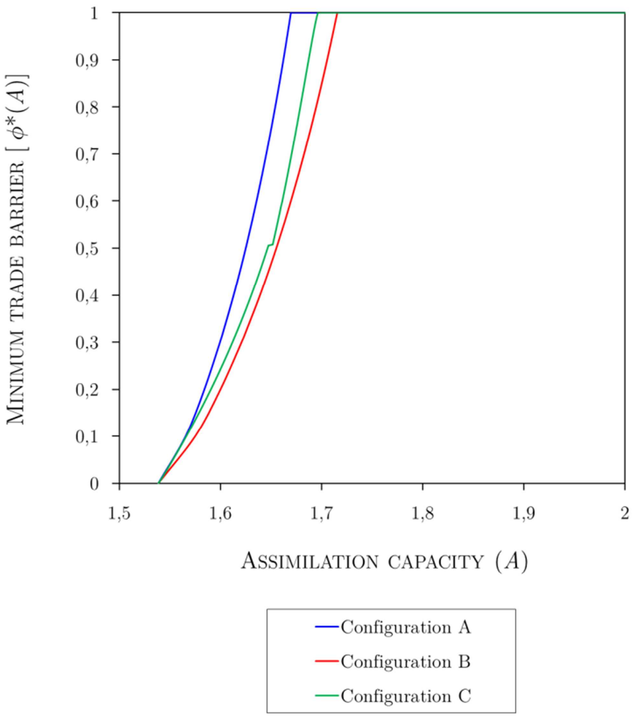

Figure I: Minimum trade barriers assuring sustainability of the spatial configurations in the context of given global pollution/GHG emissions reduction targets

For each configuration $\lambda \in \{A, B, C\}$, the stringency of the barriers to trade that are necessary to achieve sustainability is captured by the value of $\phi_\lambda^*(A)$: the higher $\phi_\lambda^*(A)$, the wider the range of trade barrier values that is compatible with sustainability for a given emission assimilation potential A and configuration λ.[13]

Figure I shows that conditional to the spatial configuration considered, free trade (defined by $\phi = 1$) can be incompatible with sustainability. The reason for this is that global emissions of pollutants reach their maximum $E_\lambda^{G,\max}$ for completely lax trade restrictions. When the emission level $E_\lambda^{G,\max}$ is higher than the pollution assimilation potential A, a more stringent trade barrier is required to meet the sustainability condition in (20), as captured by $\phi_\lambda^*(A) < 1$.

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[13] We recall that configuration λ is sustainable as long as the trade barrier ϕ satisfies $\phi < \phi_\lambda^*(A)$.

For a given value of the pollution assimilation potential A, the differences in values of $\phi_\lambda^*(A)$ across configurations illustrate that the stringency of the trade restrictions depends critically on the spatial configuration considered. In particular, it appears that $\phi_\lambda^*(A)$ is always higher for configuration A than for the two others, implying that any trade barrier that ensures sustainability of either configuration B or C also assures configuration A is sustainable.

A more detailed analysis requires a study of different A-range values over the interval $\left[A^{\min};A^{\max}\right]$, as summarized in Table 3.

Table 3: Sustainability of spatial configurations for different assimilation potentials

Spatial configuration, λ	*Value range of the (pollution, GHG) assimilation potential, A*		
	$\left[A^{\min}=1.54;1.67\right]$	$\left[1.67;1.70\right]$	$\left[1.70;1.72=A^{\max}\right]$
A	$\exists\phi$	$\forall\phi$	$\forall\phi$
B	$\exists\phi$	$\exists\phi$	$\exists\phi$
C	$\exists\phi$	$\exists\phi$	$\forall\phi$

Legend: The symbol '$\exists\phi$'denotes that the condition for sustainability is satisfied only for certain values of the trade barrier parameter (namely, $\phi<\phi_\lambda^*(A)$, with $\phi_\lambda^*(A)<1$ associated with the case $E_\lambda^{G,\min}<A<E_\lambda^{G,\max}$). The symbol '$\forall\phi$' denotes that the condition for sustainability is *always* satisfied, for any value of the trade barrier parameter (since $\phi_\lambda^*(A)=1$, associated with the case $A>E_\lambda^{G,\max}$).

In the non-trivial case $A\geq A^{\min}$, several spatial configurations potentially meet the spatial sustainability requirements summarized by condition $\phi<\phi_\lambda^*(A)$. The associated constraint on trade barriers depends on the spatial configuration considered. For example, for $1.67\leq A\leq 1.70$, three sustainable equilibria are possible: either production chooses a configuration A-like pattern (both regions feature undeveloped land use) and no constraint on trade barriers is necessary for sustainability purposes (condition: $\forall\phi$ in Table 3); or the system moves to a B- or C-like spatial configuration, in which case trade barriers must be set high enough to satisfy condition $\phi<\phi_\lambda^*(A)<1$. The policy relevance of this result is that it shows the sustainability offsetting effect between a policy imposing barrier to the volume of inter-regional or international trade and a policy inducing a reorganization of the spatial structure of regional economies.

V. Conclusion

This paper has presented and formalized the notion of 'spatial sustainability' and discussed the findings of the analytical framework from a policy-relevance perspective. To do so, it has adopted a general equilibrium model that was recently developed by Grazi *et al.* (2016), GVW shortly, based on the new economic geography (NEG). GVW included explicit land use and accounted for five drivers of the economic activity, namely: positive agglomeration spillovers; negative environmental externalities; the so-called "market-density" effect; interregional trade; and factor mobility. This model was extended here by introducing a dynamic analysis of global pollution and pollution stock effects, which has allowed to analytically address environmental sustainability.

Our approach to connect economic use of space and environmental sustainability is motivated by global environmental concerns and specifically by the potential for spatial organization, spatial planning and trade policy to act as additional strategies for controlling global climate change. In this extended version of the GVW model, we have considered the constraints imposed on long-term global environmental externalities—possibly caused by greenhouse gas (GHG) emissions—to avoid dangerous climate change. In view of uncertainties about the economic and welfare effects of climate change, we have studied alternative scenarios of policy stringency. For each scenario, we have considered three alternative spatial configurations capturing degrees of spatial concentration ('urbanization') of economic activities at the regional level and studied which environmental regulation and trade barrier are to be imposed in order to satisfy the sustainability constraint on long-term emissions.

When dynamics of global (pollution, GHG) emissions is accounted for, a main result of the analysis is that the spatially concentrated economy, while enabling strongly positive agglomeration effects on economic activity, does not necessarily perform best in terms of sustainability. The reason is that energy-intensive industrial production tends to increase when agglomeration spillovers occur, which negatively affects the regional environment due to pollution associated with energy use. A spatially concentrated economy turns out to be compatible with a sustainable economy only for a very lax constraint on long-term emissions, which reflects very high level of initially available environmental capital. A counter-intuitive finding is that a dispersion of economic activities may perform best in terms of sustainability under a very stringent constraint on emissions (and hence initially low values of the environmental capital) because of less rigid trade barriers that result from the environmental regulation and which ultimately foster economic activity.

These findings illustrate the relevance of endogenous sustainability-offsetting spatial and trade effects in environmental regulation. They can help to formulate an effective mix of policies focusing on emissions reduction, redirection of trade and spatial reorganization. Moreover, since the model approach makes a clear distinction between environmental externalities and sustainability, it adds a dynamic element to the existing literature on trade and environment. This results in a framework that can address the spatial and trade as well as policy dimensions of long-term environmental problems. In the context of climate change this means an urgently needed extra set of options to reach very ambitious emission reduction targets.

References

Benarroch, M. and Thille, H. (2001). “Transboundary Pollution and the Gains from Trade”. *Journal of International Economics*, **55**, 139–159.

Bernard, A.B., Eaton, J., Jensen, B.J. and Kortum, S. (2003). “Plants and Productivity in International Trade”. *American Economic Review*, **93**, 1268–1290.

Copeland, B.R. and Taylor, M.S. (1994). “North-South Trade and the Environment”. *Quarterly Journal of Economics,* **109**, 755-787.

Copeland, B.R. and Taylor, M.S. (1995). “Trade and Transboundary Pollution”. *American Economic Review*, **85**, 716–737.

Copeland, B.R. and Taylor, M.S. (1999). “Trade, Spatial Separation and the Environment”. *Journal of International Economics*, **47**, 137–168.

Copeland, B.R. and Taylor, M.S. (2004). “Trade, Growth, and the Environment”. *Journal of Economic Literature*, **42**, 7–71.

Dixit, A.K. and Stiglitz, J.E. (1977). “Monopolistic Competition and Optimum Product Diversity”. *American Economic Review*, **67**, 297–308.

Fujita, M. and Thisse, J-F. (2002). *Economics of Agglomeration: Cities, Industrial Location, and Regional Growth.* Cambridge University Press, Cambridge, UK.

Fujita, M., Krugman, P.R. and Venables, A.J. (1999). *The Spatial Economy: Cities, Regions, and International Trade.* MIT Press, Cambridge MA.

Gradus, R and Smulders, S. (1993). “The Trade-off between Environmental Care and Long-Term Growth-Pollution in Three Prototype Growth Models”. *Journal of Economics*, **58**, 25–51.

Grazi, F., Van den Bergh, J.C.J.M. and Waisman, H., (2016). “A Simple Model of Agglomeration Economies with Environmental Externalities”. *AFD Research Papers* (forthcoming).

Grazi, F., van den Bergh, J.C.J.M. and Rietveld, P. (2007). “Spatial Welfare Economics versus Ecological Footprint: Modeling Agglomeration, Externalities, and Trade”. *Environmental & Resource Economics*, **38**, 135–153.

IEA. (2008). *World Energy Outlook 2008.* International Energy Agency, IEA/OECD, Paris.

IPCC (2007*a*). Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007*b*). Summary for Policymakers. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Keeler, E., Spence, M. and Zeckhauser, R. (1971). “The Optimal Control of Pollution”. *Journal of Economic Theory*, **4**, 19–34.

Krugman, P.R. (1991). “Increasing Returns and Economic Geography”. *Journal of Political Economy*, **99**, 483–499.

OECD. (2007). *2007-2008 Programme of Work of the OECD Territorial Development Policy Committee.* Organization for Economic Co-operation and Development, OECD, Paris.

OECD. (2010). *Regional Development Policies in OECD Countries.* Organization for Economic Co-operation and Development, OECD, Paris.

Pezzey, J.C.V. and Toman, M.A. (2005). “Sustainability and its Economic Interpretations.” In Simpson, R.D., Toman, M.A. and Ayres, R.U. (eds.) *Scarcity and Growth: Natural Resources and the Environment in the New Millennium* RFF Press, Washington, D.C, pp 121–142

Samuelson, P.A. (1952). “The Transfer Problem and Transport Costs: The Terms of Trade when the Impediments are Absent”. *Economic Journal*, **62**, 278–304.

Unteroberdoerster, O. (2001). “Trade and Transboundary Pollution: Spatial Separation Reconsidered”. *Journal of Environmental Economics & Management*, **41**, 269–285.

Van der Ploeg, F. and Withagen, C.A. (1991). “Pollution Control and the Ramsey Problem”. *Environmental & Resource Economics*, **1**, 215–236.

Appendix

A1. Values of model parameters and exogenous variables

A1.1. Parameters and exogenous variables defining the economy

In line with the literature (Grazi *et al.*, 2016; 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) $\gamma = 1$.

A1.2. Parameters defining local pollution E_j^L and global pollution E_j^G

Concerning the local pollution parameters, the parameter a^L in eq. (12) is normalized to 1, as a definition of the unit of measure of pollution-externality flow arising from manufacturing production. As for the parameters defining the global pollution E_j^G in eq. (17), a^G is normalized to 1. The numerical value of parameter b^G is calibrated on empirical data for manufacturing production and trade. Based on estimates by the World Trade Organization and the World Bank, respectively, trade of manufacturing goods τ_{tot}^M amounted to 8, 257 Billion$ in 2006, and total industrial production x_{tot}^M to 13,428 Billion$.[14] These two activities represent, respectively, 3.5% and 25% of world greenhouse gas (GHG) emissions from energy use considered as the stock pollutant

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[14] Data from the International Trade Statistics 2007, published by the World Trade Organization, available at http://www.wto.org/english/res_e/statis_e/its2007_e/its07_toc_e.htm.

under consideration (International Energy Agency (IEA), 2008). According to (17), the amount of emissions associated with production x_{tot}^{M} and trade τ_{tot}^{M} are given by $a^{G}x_{tot}^{M}$ and $b^{G}\tau_{tot}^{M}$, respectively. The above figures on relative GHG emissions then lead to $\frac{b^{G}\tau_{tot}^{M}}{a^{G}x_{tot}^{M}} = \frac{3.5\%}{25\%} = 0.14$. This gives $b^{G} = 0.23$.

A1.3. 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. (13)] in the present paper and equations (19) and (20) in GVW model by Grazi *et al*, 2016, 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 (16). 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 equations (19) and (20) in the GVW model 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 $\frac{\beta_2}{\beta_1}$ be calibrated over some alternative trend of energy-intensity of the domestic 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.[15] The β-parameters capture these differences in energy intensity, so that we

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

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 "market form" parameter in the spatial configurations, by region

Spatial configuration, λ	*Values of the market form parameter β*	
	Region 1 $\left(\beta_1\right)$	Region 2 $\left(\beta_2\right)$
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

A2. Functional Specifications

A2.1. The "market density" effect function, $\bar{\psi}\left(n_j\right)$

Function $\bar{\psi}\left(n_j\right)$ 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: $\bar{\psi}\left(0\right) = 1$. 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 $h = H_1/H$ as the share of the regional population, the *market density* effect $\bar{\psi}\left(n_j\right)$ 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. When referring to GVW analysis in Section III, such an 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 in Grazi *et al.*, 2016), with $d_\psi^{(0.5)} = 2\mu_\psi$. This can be rewritten as $\mu_\psi > d_{\psi,0}/2$. Taking $\delta = 0.4$ and $\varepsilon = 3$, and recalling $d_{\psi,0} = 4\left(\varepsilon - 1 - \delta\right)/\delta(\varepsilon - 1)$ 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.

A2.2. 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 III in Grazi *et al.*, 2016), 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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