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Capital Heterogeneity, Industrial Clusters and Environmental Consciousness

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Abstract

It is shown in the context of a new economic geography that when capital is heterogeneous - degree of environmental sensitivity - trade liberalization may lead to industrial agglomeration and inter-regional trade. Capital heterogeneity gives local monopsony power to firms but also introduces variations in the quality of the match. Matches occur, under environmental consciousness assumption, giving rise to an agglomeration force, which can offset the forces against, trade costs and the erosion of monopsony power. A robust agglomeration equilibrium is derived analytically and shows that pollution can provide a motive for trade by spatially concentrated industries with environmental sensitivities.

• **JEL Classification:** F10, Q20, R12

• **Key Words:** Agglomeration, Pollution, Matching

I. Introduction

The link between international trade and environmental policy has been a particularly active field of research during the last years. It has been expanded rapidly and a diverse set of questions and issues has been addressed (Antweiler *et al*., 2001). This rapid growth was fuelled by a number of prominent policy debates. One of the most serious limitations is that it ignores the long run effects of industrial pollution on productivity in environmentally sensitive sectors. Copeland

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and Taylor (1994, 1995), Rauscher (1991), Petronglo and Pissarides (2000) and Beghin *et al*. (1994) are useful contributions towards this line of research. Most of the existing work assumes that pollution generates a disutility cost to the welfare of the society. As pointed out by Lopez (1994), growth and environment issues are unambiguously related, where pollution affects the production process, and thus it can make vulnerable the long run competitiveness of environmentally sensitive industries. Arguably, if trade affects pollution, then it may also affect long run income values (Bontems and Bourgeon, 2005).

In the context of new economic geography literature, agglomeration of manufacturing industries arises when combined with linkages between vertically linked firms (Krugman and Venables, 1995). Despite the apparent link between the output of heavy industry and damage to environmentally sensitive sectors, economists are often ignoring the potential role for international trade in this set up. In this paper, we demonstrate that the introduction of trade may lead to industrial agglomeration and inter-regional trade when capital is heterogeneous. Heterogeneity is defined as the distinction of capital among environmentally sensitive and insensitive inputs; and is horizontal, in the sense that no unit of capital is more productive than another. Thus, capital is differentiated relative to the degree of its environmental sensitivity. Based on the variation of that degree, heterogeneity of capital is defined and the location of the firm is chosen. Moreover, heterogeneity of capital determines the quality of the match between firms and inputs; in equilibrium each input of capital will be matched to the firm located closest to it. Consequently, heterogeneity is an essential element of the market of inputs.

The general concept of technological spillovers is probably the most frequently invoked source of agglomeration effects. Such centripetal forces enhance knowledge flows by making communication less costly. Centripetal forces are difficult to measure and we know little about the degree to which they operate within industries versus between industries (Krugman, 1991). While the prosperity of the high-technology cluster in Silicon Valley and the high-fashion cluster in Northern Italy may arise from local knowledge spillovers, less ephemeral stories involving environmentally sensitive capital may play equally important roles.

Requate and Unold (2001) mention the issue of improving environmental technology and capital investment. Following their work, this paper shows that when production externalities (Panagariya, 1981) are important, trade may in fact play a key role in determining environmental outcomes[1] by industrial agglomeration. In other words, without trade, a country or region has to produce what it consumes and so environmentally sensitive industries may have their productivity impaired by centrifugal forces, such as pollution from other sectors of the economy (Nannerup, 2001).

A survey of the British Air Transport Association (Bata), the trade body for UK airlines, reports that more than 20 million people reduced their air travel because of concern about climate change (*The Independent*; February 10, 2007). Moreover, there is already ample empirical evidence linking industrial pollution to reduced fishing and agricultural yields, to negative effects on the value of standing forests, and to beach closures that hurt tourism. Gallagher and Taylor (2003) analyze the period 1993 to 2001 and find that the economic costs of CO_2 pollution in United States are estimated to be \$1.1 billion or \$126 million per year. Those estimates of environmental damage suggest that centrifugal forces are neither negligible, nor unobtrusive, and create a society with environmental consciousness.

The paper extends the results of Copeland and Taylor (1999) by using the concept of environmental consciousness as an instrument of industrial agglomeration. Thus, environmental consciousness is directly related to centripetal / centrifugal forces. The country which ends up with the polluting industry may suffer not only from reduced productivity in environmentally sensitive sectors,[2] but also from terms of trade deterioration that is brought on by its own environmental degradation (Helpman, 1984). The latter degradation motivates the environmental consciousness of both consumers and firms. In turn, firms maximize their profits should they adopt environmentally friendly inputs. However, as firms congregate, the location becomes less attractive since competition among users bids up the price of the input. A corresponding phenomenon could occur on the demand side if exogenous forces promote the concentration of downstream demand for a particular industry. These considerations suggest an important difference between the theories: agglomeration benefits result from various centripetal forces, but from different environmental consciousness levels, receiving very dissimilar shares of investment in any particular industry. This study estimates the magnitude of

[1]Estimating environmental costs (and benefits) of economic activity for society can be challenging because they do not often lend themselves to monetary valuation (Arrow, 2000).

[2]See Grossman and Krueger (1993) for empirical work. For theory, see Markusen (1975, 1976); Copeland and Taylor (1994, 1995), and Rauscher (1991).

environmentally sensitive industry-level effects and assesses their importance about location decisions (Das, 2001).

In what follows we uncover a number of interesting parallels and contrasts between the implications of these two different, but similar, motives for trade. Section II describes the model and the capital market. Aggregate equilibrium is characterized in section III and section IV provides some concluding remarks.

II. The Model

The strategic trade policy analysis of Brander and Spencer (1985) put the trade and environment debate[3] into a different perspective. The basic argument is developed by Barrett (1994), Conrad (1993) and Kennedy (1994). Based on their contribution, we present a model to make transparent the role trade can play in industries with heterogeneous capital. There are two countries (or regions; home and foreign) and two industries: a manufacturing industry (M) and an environmentally sensitive industry such as tourism (T). We differentiate capital in environmentally sensitive and insensitive (heterogeneity).

We define "environmentally sensitive capital" as an input which is meant to capture the productivity-relevant aspects of environmental quality standards. The manufacturing industry emits pollution, and over time the flow of these pollutants degrades the society's environmental capital. Since we assume that the free flows of services from the environment are inputs into tourism industry, a lower stock of environmentally sensitive capital necessarily lowers the productivity of other primary inputs in the tourism industry. Three basic assumptions are used: (a) pollution stays within the country of origin and emissions do not create a direct utility cost to consumers, (b) there is perfect inter-sectoral (but not inter-regional) mobility of capital and labor, although transforming environmentally insensitive to environmentally sensitive capital inputs requires some fixed adjustment cost, and (c) there is perfect inter-sectoral and inter-regional mobility of firms.

The tourism industry produces a single good but there are many differentiated manufacturing goods, each produced by one firm only. Consumers have Dixit-Stiglitz preferences over the manufacturing goods, which are represented by a composite vector, denoted by C_M. Consumption of the tourism good is denoted by . The utility function of individual q is given by

[3]An insightful technical survey of this literature is contained in Ulph (1997).

$$U_q = \theta_q C_{Mq}^{\eta} C_{Tq}^{1-\eta} \tag{1}$$

where $\eta[\in(0,1)]$ denotes elasticity of substitution of the two goods and θ_q is the fixed effect from the industry in which individual works. Assuming that k is the number of goods produced domestically and k' abroad[4] we define the utility function for manufacturing goods as

$$C_{Mq} = \left[\sum_{i=1}^{K} c_{iq}^{\frac{\mu-1}{\mu}} + \sum_{j=1}^{K'} \left(\frac{\pi_{jq}}{\xi}\right)^{\frac{\mu-1}{\mu}}\right]^{\frac{\mu}{\mu-1}} \tag{2}$$

where c_{iq} is the consumption of the domestic manufacturing good i, π_{jq} is the demand for the foreign manufacturing good j, μ denotes elasticity of substitution among differentiated manufacturing goods and ξ resembles transportation cost. The budget constraint (I) of individual q is

$$I_q \geq \sum_{i=1}^{K} h_i c_{iq} + \sum_{j=1}^{K'} h_j' \pi_{jq} + h_T c_{Tq} \tag{3}$$

with h denoting an element of the vector of prices (H) and thus the price index of manufacturing good is

$$H_M = \left[\sum_{i=1}^{K} h_i^{1-\mu} + \sum_{j=1}^{K'} (\xi h'_j)^{1-\mu}\right]^{\frac{1}{1-\mu}} \tag{4}$$

Subsequently, the individual demand functions for domestic and foreign manufacturing goods are given by maximization of utility function (1)

$$c_{iq} = \eta\left(\frac{h_i}{H_M}\right)^{-\mu} \frac{I_q}{H_M} \tag{5}$$

and,

$$\pi_{jq} = \eta\left(\frac{\xi h_i'}{H_M}\right)^{-\mu} \frac{\xi I_q}{H_M} \tag{6}$$

where η is the elasticity of substitution among manufacturing and tourism goods as defined in equation (1). As a result, we define (by adding 5 and 6) the demand constraint facing a domestic firm as

$$m_i = \eta h_i^{-\mu}(H_M^{\mu-1} I + \xi^{1-\mu} H'^{\mu-1}_M I') \tag{7}$$

[4]We denote with " ′ " (prime) the foreign economic variables.

where m_t is the total demand for good i. Firms in manufacturing industry are monopolistic competitors and maximize their profit function subject to the demand constraint. The numeraire good is considered to be the output of tourism industry. The environmentally sensitive capital used by firms is denoted by $F_s^i(r_i)$, which is differentiable, and r_i its rate of return. In contrast, there is no differentiation at the nature of labor input; inelastic labor supply. Thus, E_i (w_i) is the employment level of the firm, with w_i, the corresponding wage level. The production function defined as

$$m_i(F_s^i, L_i) = \sigma + \rho F_s^i + \zeta L_i \tag{8}$$

satisfies all the conditions implied by new trade theory, except that there are heterogeneities in the performance of capital. Parameter σ denotes the autonomous part of production function, and, parameters ρ and ζ refer to the elasticities of environmentally sensitive capital (F_s) and land input (L), respectively. Firms in industrial sector maximize profit (z) by

$$z_i = h_i m_i - r_i F_s^i(r_i) - w_i L(w_i) \tag{9}$$

The first order conditions produce the following mark-up equation

$$h_i = \frac{\mu\rho}{\mu - 1}\left(1 + \frac{1}{\varepsilon_i^s}\right) r_i \tag{10}$$

where all parameters have been defined in equations 1-9 but ε^s which denotes the elasticity of the supply of capital. Equilibrium output level is derived when we substitute equation (10) into (7). We now turn the discussion to the supply of the differentiated capital.

A. Environmental Sensitivity and Choice of Capital

Both in the international trade and environment literature, non-convexities play a central role. Many authors have modeled increasing returns as a positive externality external to firms, but internal to an industry (Helpman, 1984). This generates potential centripetal forces from trade from concentrating industries with external economies in one location. It is well known that pollution externalities lead to non-convexities in the production set (Baumol and Bradford, 1972). While this result is well known, it has had relatively little impact on the mainstream of the environment literature. In line with recent work by Copeland and Taylor (1999), we show that non-convexities generated by pollution externalities can play a critical role in determining the pattern of trade and the environmental consequences of free trade.

The environmental sensitivity of capital determines the quality of their match with firms. We model the quality of a match as an one-dimensional measure which we call the "distance" (denoted by a) of the capital from the firm (Helsley and Strange, 1990). Degrees of environmental characteristics of capital are distributed along a circular grid, whose circumference is of length $2S$. S shows how far match-specific productivities can vary from each other. If $S = 0$ there is no heterogeneity and the input of capital has the same productivity in all firms. Allocation of environmentally sensitive capital is randomly on this circle, with all locations equally likely. In contrast, firms can choose their location.

Proposition 1. *The closer a firm to an input of capital with environmental sensitivity the better the quality of their match.*[5]

In equilibrium each input of capital will be matched to the firm located closest to it. Assuming that all firms (K) locate symmetrically along the circular grid, it follows that the distance[6] between any two firms is 2S/K and so the worst case of mismatch (v) is half the distance, S/K. To derive the corresponding rate of return of capital, assume that firm[7] i is located in between two other firms that post return r. Capital inputs located at the left of i will be absorbed and supply $1\text{-}a$ units of capital or alternatively $1\text{-}(2v\text{-}a)$ units. Consequently, firm i provides a return of capital r_i and the input of capital is employed by firm i should

$$r_i(1-a) \geq r(1-(2v-a)) \tag{11}$$

with the maximum distance a, that satisfies inequality (11), to be given by

$$a_i = \frac{r_i - r(1-2v)}{r_i + r} \tag{12}$$

[5]Firms are more likely to get capital the further away they are from other firms, unless they locate exactly at the same point as another firm and beat its return. But in the latter case, Bertrand competition will lead to the equality between the posted return and the value of marginal product of capital. Once firms deviate, Cournot?Nash competition leads to symmetric locations along the circle.

[6]The mechanism of locational choice is similar to the one presented by D' Aspremont *et al*. (1979).

[7]Firms post r return for each effective unit of capital, so the highest rate in the market is r and the lowest the one offered to the most distant input of capital is r(1- v).

Since inputs of capital are uniformly distributed on the circular grid, a_i / S units of environmentally sensitive capital are used by firm and the average number of environmentally sensitive units of capital per capital is 1-a_i/2. Subsequently, the total number of units of environmentally sensitive capital ($F_s^i(r_i)$) supplied to the firm is a function of total number of units of capital ($F^i(r_i)$) and is given by

$$F_s^i(r_i) = \frac{a_i}{S}\left(1 - \frac{a_i}{2}\right)F^i = \frac{F^i}{2S}\frac{(r_i - r + 2vr)(r_i + 3r - 2vr)}{(r_i + r)^2} \tag{13}$$

The supply[8] of environmentally sensitive capital to each firm in symmetric equilibrium is derived from equation

$$F_s^i = \frac{F^i}{K}\left(1 - \frac{v}{2}\right) \tag{14}$$

Given the latter setup of the model, the elasticity of the supply of capital in symmetric equilibrium is:

$$\varepsilon_i^s = \left.\frac{dF_s^i}{dr_i}\frac{r_i}{F_s^i}\right| r_i = r = \frac{(1 - v)^2}{(2 - v)v} \tag{15}$$

B. Capital Market

All firms set the same price, therefore have the same demand for output and so employ the same number of workers. This confirms the existence of the symmetric equilibrium.

Proposition 2. A *higher mismatch ratio (v) implies that firms are located further away from each other, competition is less intense and so the markup of prices over return of environmentally sensitive capital is higher.*

We represent the capital market equilibrium for a given allocation of a unit of environmentally sensitive capital to the manufacturing sector with F_s^i. The capital market equilibrium is defined by substituting equation (15) into equation (10) and imposing symmetry

$$h_i = \frac{r}{(1 - v)^2}\frac{\mu\rho}{\mu - 1} \tag{16}$$

[8]Additionally, the partial derivative of equation (13) with respect to r is positive, confirming that the firm faces an upward-sloping labor supply curve.

The corresponding quantity supplied of the composite manufacturing good is defined using equations (8) and (16),

$$m_i = \frac{\sigma(\mu-1)}{\rho}\frac{(1-v)^2}{\mu-(\mu-1)(1-v)^2} \tag{17}$$

The typical equilibrium found in this model, allows each firm's output not to depend only on parameters. By substituting equation (17) into equation (8) we obtain the demand for environmentally sensitive capital units by each manufacturing firm,

$$F_s^{Di}(v) = \frac{\sigma\mu}{\mu-(\mu-1)(1-v)^2} \tag{18}$$

Supply of environmentally sensitive capital units is defined by equation (14), or in terms of v:

$$F_s^{Si}(v) = \frac{F^i}{S}v(1-\frac{v}{2}) \tag{19}$$

It is obvious[9] that a necessary and sufficient condition for a unique equilibrium v is that at the maximum feasible v, F_s^{Si} exceeds F_s^{Di}. The later is always true if the density of the environmentally sensitive capital units on the circular grid, F_s / S, is sufficiently large. At $S = 0$, $v = 0$ the equilibrium number of firms is given by

$$K = \frac{F_s}{\sigma\mu} \tag{20}$$

The unique equilibriumcan be obtained as the only nontrivial solution to the equation $F_s^{Si} = F_s^{Di}$. The resulted quadratic equation is defined as

$$2(\mu-1)v^2\left(1-\frac{v}{2}\right)^2 - \frac{\sigma\mu S}{F_s} = 0 \tag{21}$$

It is straightforward that the root of equation (21) below unity is the unique equilibrium v.

[9]Differentiation of equations (18) and (19) results in $F_s^{Di}(v) < 0$ and $F_s^{Si}(v) > 0$.

III. Aggregate Equilibrium

We obtain an explicit analytical solution for the equilibrium allocations under the simplifying assumptions that the two regions are of equal size. The supply of labor and corresponding wages do not have any impact on the equilibrium since they are not characterized by any heterogeneity. Henceforth, an aggregate equilibrium[10] is an allocation of capital across sectors; and an allocation of firms across sectors and regions that satisfy utility, profit maximization and market clearing.[11] The aggregate equilibrium pricing equation for manufacturing goods is derived from equations (16) and (21) and the assumption of equality in utility levels

$$h_i = \frac{R_s}{(1-v/2)(1-v)^2}\frac{\mu\rho}{\mu-1} \tag{22}$$

which is an implicit function of R_s (the mean return received by inputs of capital).

The allocation of capital (F) across sectors is associated with the national income (NI). In our case, national income is defined as

$$NI = F+(R_s-1)R_s \tag{23}$$

Trade conditions imply that the output of each manufacturing firm has to satisfy both domestic consumption and exports. Using equations (4) and (29) with the demand function [equation (7)], the bundle $\{x,x'\}$of demand for manufacturing output

$$\left\{\eta h^{-\mu}\left[\frac{(R_s-1)F_s+F}{Kh^{1-\mu}+K'(\xi h')^{1-\mu}}+\frac{\xi^{1-\mu}[(R_s^{'}-1)F_s^{'}+F^{'}]}{K(\xi h)^{1-\mu}+K'h'^{1-\mu}}\right],\right.$$

$$\left.\eta h'^{-\mu}\left[\frac{\xi^{1-\mu}[(R_s-1)F_s+F]}{Kh^{1-\mu}+K'(\xi h')^{1-\mu}}+\frac{(R_s^{'}-1)F_s^{'}+F^{'}}{K(\xi h)^{1-\mu}+K'h'^{1-\mu}}\right]\right\} \tag{24}$$

We substitute x from equation (24) and F_s from equation (14) into equation (9),

[10]It is assumed that the expected utility of those in manufacturing sector is equal to those who work at tourism sector. The equality of the utility levels implies that $R_s = r(1\text{-}v/2)$; the mean return received by inputs of capital (Rotemberg and Saloner, 2000).

[11]Assuming η<0.5 is a sufficient condition to obtain solution for the equilibrium allocation.

under the assumption of equality of utility levels and we obtain an expression for the domestic[12] country:

$$\frac{(R_s-1)F_s+F}{1+\xi^{1-\mu}\left[\frac{v}{v'}\left(\frac{h}{h'}\right)^{\mu-1}\right]}+\frac{\xi^{1-\mu}[(R_s'-1)F_s'+F']}{\xi^{1-\mu}+\frac{v}{v'}\left(\frac{h}{h'}\right)^{\mu-1}}=\frac{R_sF_s}{\eta} \tag{25}$$

A symmetric equilibrium in each country exists and we may obtain its characterization through equation (25). Given symmetric conditions, it is $F=F'$, $F_s' = F_s$, $R_s' = r(1-v/2)$ and $\frac{v}{v'}\left(\frac{h}{h'}\right)^{\mu-1} = 1$. Therefore, it is

$$F_s = \frac{\eta}{r(1-v/2)-[r(1-v/2)-1]\eta}F \equiv \hat{\eta}F \tag{26}$$

Subsequently, we define the firm's price (from equation (22)) and the output (from equation (30)) given the latter equilibrium conditions as

$$h_i = \frac{r(1-v/2)}{(1-v/2)(1-v)^2}\frac{\mu\rho}{\mu-1} \tag{27}$$

$$x_i = \frac{\eta F[r(1-v/2)]^2}{S(1-v/2)(1-v)^2}\frac{\mu\rho v}{\mu-1} \tag{28}$$

Mobility of firms implies that with trade there is at least one other equilibrium, with all firms locating in one country and selling their goods to both countries. We characterize the agglomeration equilibrium by assuming that all manufacturing output is concentrated in the home country. Substitution of these values and $R_s = r(1\text{-}v/2)$into equation (25) yields a solution for F_s that is very similar to the symmetric solution:

$$F_s = \frac{\eta(F+F')}{\eta+(1-\eta)r(1-v/2)} \tag{29}$$

Having shown that both symmetric and agglomeration equilibrium exist, a selection among those is a critical aspect. In other words, is the suggested capital heterogeneity strong enough to give an incentive to firms to deviate from the

[12]A similar expression holds for the foreign country:

$$\frac{\xi^{1-\mu}[(R_s-1)F_s+F]}{\xi^{1-\mu}+\frac{v}{v'}\left(\frac{h}{h'}\right)^{\mu-1}}+\frac{(R'_s-1)F'_s+F'}{1+\xi^{1-\mu}\left[\frac{v}{v'}\left(\frac{h}{h'}\right)^{\mu-1}\right]}=\frac{R_sF_s}{\eta}$$

symmetric equilibrium when there is trade? We adapt the stability criterion suggested by Fujita *et al*. (1999) in a related context to answer this question.

Proposition 3. *For sufficiently low increase of amount of environmentally adjusted capital in the home country, there is a stable equilibrium point (break point), should the symmetric impact on return of capital in both countries generates a negative response of equilibrium mean manufacturing return (R) with respect to the supply of capital (F).*

Proof. See the Appendix.

Beginning with the symmetric equilibrium with trade, an increase of the amount of capital in the home country and will generate a decrease in the foreign country by the same amount. We look for the level of trade costs (break point) at which this increases the return rate in the home country and reduces it in the foreign country (Fujita *et al*., 1999). Equation (29) may be written as $F_s = 2\overset{\leftrightarrow}{\eta}F$ and, thus, by totally differentiating[13] equation (25) we get

$$\frac{\overset{\leftrightarrow}{\eta}F}{\eta}dR_s + \frac{R_s'}{\eta}dF_s = \frac{1-\xi^{1-\mu}}{1+\xi^{1-\mu}}[(R_s'-1)dF_s + \overset{\leftrightarrow}{\eta}FdR_s] - \frac{2\xi^{1-\mu}R_s'\overset{\leftrightarrow}{\eta}F}{\eta(1+\xi^{1-\mu})^2}d\psi \quad (30)$$

The first component $\{\frac{1-\xi^{1-\mu}}{1+\xi^{1-\mu}}[(R_s'-1)dF_s + \overset{\leftrightarrow}{\eta}FdR_s]\}$ is independent of our model specifications and has a negative sign (Appendix). The suggested specifications are included in the second component $\{\frac{2\xi^{1-\mu}R_s'\overset{\leftrightarrow}{\eta}F}{\eta(1+\xi^{1-\mu})^2}d\psi[=G(\xi)]\}$ and the point of interest is to explore its sign and magnitude with respect to the first component (Appendix).

Proposition 4. *Assuming that a break point for the symmetric equilibrium exists, and this leads all manufacturing firms to agglomerate in the home country, then the agglomeration equilibrium is sustainable.*[14]

Proof. See the Appendix.

Appendix (Equation (42)) shows that dv/dF_s is strictly negative and independent of ξ, so $G(\xi)\geq 0$. By differentiation we find that $G'(\xi)<0$ and $\lim_{\xi\to\infty}G(\xi) = 0$. So at very high trade costs symmetry is not broken. The maximum value[15] reached

[13]For details see Appendix.

[14]The maximum level of trade costs at which the agglomeration equilibrium becomes unsustainable is termed the "sustain point".

[15]Appendix shows that for sufficiently large G(1), Eq. (30) is positive; so in free trade our externalities are strong enough to break the symmetric equilibrium.

by $G(\xi)$ is in free trade, ξ=1. Therefore, by monotonicity, there is a critical value of ξ>1 which makes the differential dR_s/dF_s=0. This critical value of ξ is the break point and is denoted by ξ*. Our symmetric equilibrium is robust to deviations if $\xi \geq \xi^*$ but breaks when $\xi < \xi^*$.

We use numerical simulations[16] to illustrate how this critical level ξ^* depends on the following key parameters: the relative population rate (foreign/home), degree of heterogeneity, adjustment cost of environmentally sensitive capital, and the size of the manufacturing sector (Table 1 and Table 2). We consider an initial condition with sufficiently high trade costs and examine whether one firm can profitably deviate from the foreign to the home country. By reducing trade costs in small steps and we look for the critical value that switches the equilibrium from symmetry to agglomeration. In our initial case[17] the break point is $\xi^* = 1.44$ ($\eta = 0.3$) should countries are of similar population size, *i.e.*, when trade costs fall below 44% of the producer price, firms could break the symmetric equilibrium by

Table 1. Equilibrium Points for Similar Population Size Countries

P	L_s'	S	$\eta = 0.3$		$\eta = 0.9$	
			ξ^*	ξ^{**}	ξ^*	ξ^{**}
1.0	1.45	1.5	1.86	4.11	1.78	3.21
1.0	1.30	1.5	1.73	3.83	1.68	3.09
1.0	1.15	1.5	1.65	3.35	1.62	2.77
1.0	1.45	1.0	1.52	2.57	1.51	2.52
1.0	1.30	1.0	1.44	2.31	1.38	2.41
1.0	1.15	1.0	1.35	1.94	1.29	2.29
1.0	1.45	0.5	1.26	1.74	1.22	2.26
1.0	1.30	0.5	1.19	1.41	1.17	2.14
1.0	1.15	0.5	1.16	1.35	1.15	1.97

Note: At trade costs below ξ^* the symmetric equilibrium is violated and at points above ξ^{**} is not stable. P denotes relative population ratio, L_s' adjustment cost of environmentally sensitive capital, S the degree of capital heterogeneity and η the size of manufacturing sector.

[16]The initial values of specific parameters for all simulations are: μ=0.35, $\sigma=1/\mu$, $\rho=(\mu-1)/\mu$, S=1, and $P = p'/p$, with P denoting relative population ratio. Also, adjustment cost of environmentally sensitive capital $L_s' = 1.3$. Finally, the original number of firms is in each country 60.

[17]The break point is $\xi^* = 1.38$ and $\eta = 0.9$

relocating from the foreign country to the home country.[18]

Lower environmental adjustment cost of capital gives more incentives to firms to enter the market and so the benefits from agglomeration need to be stronger to make firms give up manufacturing in the foreign market. However, the elasticity with which the critical trade cost responds to changes in cost is small. If the manufacturing sector is larger the break point is lower. In the initial case, increasing the manufacturing sector from $\eta = 0.3$ to $\eta = 0.9$ reduces the break point from 1.44 to 1.38.

An interesting result is that the break point is very sensitive to population and country size as presented in Table 2. If foreign country is 40% bigger (P=1.4) than the home country, the break point in the home country is close to free trade in virtually all cases but the break point in the foreign country increases substantially, to 1.67 in the initial case. This implies that foreign economies should be characterized by a lot more agglomeration than home economies. This is because the source of agglomeration arises in the environmentally sensitive capital market and not in the product market, so the benefit of locating in a country with a larger pool of environmentally adjusted capital could outweigh the benefit of locating in a

Table 2. Equilibrium Points for Different Population Size Countries

P	L_s'	S								
			$\eta = 0.3$				$\eta = 0.9$			
			Home	Foreign	Home	Foreign	Home	Foreign	Home	Foreign
			ξ^*	ξ^*	ξ^{**}	ξ^{**}	ξ^*	ξ^*	ξ^{**}	ξ^{**}
1.4	1.45	1.5	1.21	1.92	4.65	4.96	1.81	2.22	5.96	6.12
1.4	1.30	1.5	1.21	1.81	4.54	4.87	1.81	2.12	5.86	6.02
1.4	1.15	1.5	1.21	1.75	4.47	4.7	1.81	1.99	5.75	5.55
1.4	1.45	1.0	1.21	1.68	3.63	3.68	1.81	1.95	4.63	4.84
1.4	1.30	1.0	1.21	1.67	3.61	3.64	1.81	1.92	4.55	4.73
1.4	1.15	1.0	1.0	1.51	3.55	3.59	1.5	1.83	4.43	4.61
1.4	1.45	0.5	1.0	1.48	3.48	3.51	1.5	1.75	4.37	4.58
1.4	1.30	0.5	1.0	1.44	3.37	3.42	1.5	1.68	4.21	4.55
1.4	1.15	0.5	1.0	1.41	3.31	3.39	1.5	1.61	4.11	4.46

Note: At trade costs below ξ^* the symmetric equilibrium is violated and at points above ξ^{**} is not stable. P denotes relative population ratio, L_s' adjustment cost of environmentally sensitive capital, S the degree of capital heterogeneity and η the size of manufacturing sector.

[18]The level of trade costs necessary to break the symmetric equilibrium is lower for lower levels of heterogeneity and lower levels of training costs (Burrows, 1986). Lower heterogeneity reduces the potential matching benefits from capital pooling, so the benefits from agglomeration are weaker.

large market for goods.[19]

Proposition 5. *Agglomeration equilibrium is robust to small deviations at trade costs below the break point.*

We suppose that all firms are located in the home country, and allow a single manufacturing firm to establish itself in the foreign country. We then calculate the optimal amount of environmentally adjusted capital that this firm will employ and its optimal return. We check whether the firm makes zero profit and should the return is above $L_s^{'}$.

Let $R_s^{'}(\xi)$ be the maximum (zero-profit) return rate of capital that the single firm in the foreign country can offer. The agglomeration equilibrium is sustainable at some level of trade costs ξ if at this level $R_s^{'}(\xi) < \frac{r}{1-v/2}$. But at higher trade costs the zero-profit wage should rise until a wage is found such that $R_s^{'}(\xi^{**}) < \frac{r}{1-v/2}$. The level of trade costs that gives that return of capital, ξ^{**}, is the sustain point for the agglomeration.

Capital utilization in the agglomeration equilibrium is given by equation (29) for the home country. Substituting these values into equation (24) we obtain the foreign firm's demand at some price h':

$$m^{'} = h^{'-\mu}\frac{\eta F}{Nh^{1-\mu}}\{\xi^{1-\mu}[R_s-1)\overset{\leftrightarrow}{\eta}+1]+\xi^{\mu-1}\} \tag{31}$$

Let $F_s^{'} > 0$ be the amount of capital that the firm wants to employ. Since the firm is the only one located on the circular grid, the number of efficiency units of capital supplied to the firm is $F_s^{'} = F'(1-S/2)$. The firm chooses h' to maximize profit, given that its employment level is optimally chosen. For any r' the profit maximizing price is given by (see Appendix)

$$h' = \frac{\rho\eta}{\eta-1}r' \tag{32}$$

The maximum return rate (r') per unit of environmentally adjusted capital at foreign country is defined should we set profits to zero:

$$r^{'} = \frac{\eta-1}{\rho\eta}\left[\frac{\sigma(\eta-1)}{\rho}\frac{Nh^{1-\mu}}{\eta F\{\xi^{1-\mu}[R_s-1)\overset{\leftrightarrow}{\eta}+1]+\xi^{\mu-1}\}}\right]^{-\frac{1}{\eta}} \tag{33}$$

Since the equality of the utility levels implies that $R_s = r(1\text{-}v/2)$ then,

[19]From Table 1, we see that in the benchmark case at trade costs at or below $\xi^* \leq 1.21$ (or at $\xi^* \leq 1.81$), the agglomeration can locate in the smaller home country.

$$r' \geq \frac{r(1 - v/2)}{1 - S/2} \tag{34}$$

which turns agglomeration equilibrium to unsustainable. The sustain point ξ^{**} is the level of trade costs that satisfies equation (34) with equality, given equation (33). However, because r' in equation (33) first falls and then rises in ξ, there is a unique and well-behaved sustain point only if the free trade equilibrium is sustainable. In order to show that the agglomeration equilibrium is sustainable we therefore need to show that $\{\xi^{1-\mu}[R_s - 1)\overset{\leftrightarrow}{\eta} + 1] + \xi^{\mu-1}\}$ for $R_s = 1$ violates equation (34), and that there is a sufficiently high value of ξ that satisfies equation (34).The second condition refers to the satisfaction of equation (34). As $\xi \to \infty$, and $\{\xi^{1-\mu}[R_s - 1)\overset{\leftrightarrow}{\eta} + 1] + \xi^{\mu-1}\} \to \infty$, equation (34) is satisfied. It therefore remains to show that at $\xi = 1$, equation (34) is not satisfied. Appendix shows that at small feasible values of v this is indeed the case. Actually, as firms agglomerate there is more competition between them and more proximity to inputs of capital reduces mismatch. If v is small the equilibrium is sustainable, since it measures the distance between firms in the agglomeration case. But if it is large, it may be profitable for a firm to forego the benefits of agglomeration and establish in the foreign country where there is no competition from other firms.

The sustain point appears to be generally more responsive to parameter changes than the break point is. In general, the sustain point is higher than the break point, so there are levels of trade costs which make both the symmetric and the agglomeration equilibrium robust to small deviations. In our initial case both equilibrium are robust at trade costs between 1.44 and 2.31 when $\eta = 0.3$ (or, between 1.38 and 2.41 when $\eta = 0.9$). Once an agglomeration is established, it is sustainable over a large range of trade costs, giving rise to persistence in location patterns as shown by numerical simulations. We examine whether 15% of all firms located in the home country would find it profitable to relocate in the foreign country. The results are shown in Table 1 and Table 2. In our initial case, the critical value of trade costs that induces relocation is 2.31, but when trade costs exceed this value, the agglomeration equilibrium is not sustainable.

IV. Conclusions

Heterogeneity of capital could be a force for agglomeration of economic activity, even when the heterogeneity gives monopsony power to firms. A key figure to our model is that firms prefer to enter a market that already has a large pool of inputs of environmentally adjusted capital. However, if trade costs are sufficiently high to make it more profitable for firms to locate in the market that they supply, rather than in the market that their capital productivity is highest, agglomeration fails. The results are in line with Copeland and Taylor (1999) who develop a simple two-sector dynamic model to show how pollution can provide a motive for trade by spatially separating incompatible industries but they do not extent their discussion to the agglomeration aspect.

Many environmentalists and economists (Fujita *et al*., 1999; Helfand and Rubin, 1994; Rosental and Strange, 2001) state that trade allows for the spatial separation of dirty product consumers and dirty product producers; we find that such separation can bring centripetal forces in terms of production efficiency. Accordingly, we find that the type of separation matters and several interesting results follow: two countries can engage in mutually beneficial trade; trade will be mutually beneficial if the demand for the polluting good is high. The intuition for many of our results is straightforward. Without trade, a country or region has to produce what it consumes and so environmentally sensitive industries may have their productivity impaired by centrifugal forces such as pollution from other sectors of the economy. Centripetal forces, such as trade, can play a useful role in allowing incompatible industries to move away from each other, as it is also suggested by (Antweiler *et al*., 2001). By creating agglomeration externalities, trade can reduce the damage from cross-sectoral production externalities and can generate productivity gains for the world as a whole, as it is suggested by Leger (1995). The benefits of higher global productivity may not be shared across all countries, however, because the productivity changes also bring forth terms of trade changes.

Our analysis has further testable implications and a necessary next step is to look for these in the data. Two forces in particular appear to be consistent with casual observation: that there should be dissimilar levels of agglomeration in industries with differentiated centripetal forces; technological standards, and that agglomeration should increase as trade costs come down and as the complexity of centrifugal forces increases.

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Appendix

Throughout this Appendix, we derive the proofs of propositions (3) and (4).

Proof of proposition 3:

From equation (25), we define

$$\psi = \frac{v}{v'}\left(\frac{h}{h'}\right)^{\mu-1} \tag{A1}$$

By totally differentiating equation (25) and using equation (A1) we have

$$\frac{\overleftrightarrow{\eta}F}{\eta}dR_s + \frac{R_s}{\eta}dF_s = \frac{1-\xi^{1-\mu}}{1+\xi^{1-\mu}}[(R_s'-1)dF_s + \overleftrightarrow{\eta}FdR_s] - \frac{2\xi^{1-\mu}R_s'\overleftrightarrow{\eta}F}{\eta(1+\xi^{1-\mu})^2}d\psi \tag{A2}$$

We differentiate equation (A1) and equation (22) to get equations (A3) and (A3), respectively:

$$d\psi = \psi(\cdot)\left[\left(\frac{1}{v}+\frac{1}{v'}\right)dv + (\mu-1)\left(\frac{1}{h}+\frac{1}{h'}\right)dh\right] \tag{A3}$$

$$dh = \frac{h}{R_s}dR_s + \frac{1-v+2(2-v)}{(2-v)(1-v)}hdv \tag{A4}$$

Substituting equation (A4) into equation (A3):

$$d\psi = \psi(\cdot)\left\{\left[\left(\frac{1}{v}+\frac{1}{v'}\right)dv + h(\mu-1)\left(\frac{1}{h}+\frac{1}{h'}\right)\frac{1-v+2(2-v)}{(2-v)(1-v)}\right]dv + (\mu-1)\right.$$

$$\left.\left(\frac{1}{h}+\frac{1}{h'}\right)\frac{h}{R_2}dR_s\right\} \tag{A5}$$

By symmetry we have that

$$d\psi = (\mu-1)\frac{2}{R_s}dR_s + 2\left[\frac{1}{v} + (\mu-1)\frac{1-v+2(2-v)}{(2-v)(1-v)}\right]dv \tag{A6}$$

We differentiate equation (21) to get *dv*

$$dv = -\frac{\sigma\mu S}{F_s^2}\frac{1}{(1-v)[2(\mu-1)v(2-v)+1]}dF_s \tag{A7}$$

Equation (A7) is rewritten, should we replace $\frac{\sigma\mu S}{F_s^2}$ and use $F_s = 2\overleftrightarrow{\eta}F$,

$$dv = -\frac{1}{2\overleftrightarrow{\eta}F}\frac{v(2-v)[(\mu-1)v(2-v)+1]}{(1-v)[2(\mu-1)v(2-v)+1]}dF_s \tag{A8}$$

Substituting *dv* from equation (A8) into equation (A6) and the resulting $d\psi$ into equation (A2), we manage to identify the sign of the entire expression. Actually, we collect all terms that contain dR_s to the left hand side and the terms that contain dF_s to the right hand side. The coefficient multiplying dF_s in the right hand side is shown in equation (30). The coefficient multiplying dR_s in the left hand side is:

$$\overleftrightarrow{\eta}F\left(\frac{1}{\eta} - \frac{1-\xi^{1-\mu}}{1+\xi^{1-\mu}}\right) + \frac{2\xi^{1-\mu}[(R_s-1)\overleftrightarrow{\eta}+1](\mu-1)2F}{\eta(1+\xi^{1-\mu})^2 R_s} \tag{A9}$$

Recalling that $\eta<1$, $\mu>1$ and $\xi\geq 1$, the first component of equation (A9) is positive and henceforth the sign of $\frac{dR_s}{dF_s}$ will depend on the sign of dF_s as shown in equation (30).

In order to show that G(1) in equation (30) is sufficiently large to make the entire expression positive we use equations (30) and (A8) to write G(ξ) as:

$$G(\xi) = [1+v(\mu-1)(2-v)]\frac{2R_s\xi^{1-\mu}}{\eta(\xi^{1-\mu}+1)^2}\frac{(2-v)(1-v)+(\mu-1)[v(1-v)+2v(2-v)]}{(1-v)^2[1+2v(\mu-1)(2-v)]} \tag{A10}$$

Under free trade conditions ($\xi = 1$) the term $\frac{2R_s\xi^{1-\mu}}{\eta(\xi^{1-\mu}+1)^2} = \frac{R_s}{\eta}$, as is the sum of

the first two terms of equation (30), and thus the sign of the entire expression in equation (30) is the same as the sign of

$$\frac{R_s}{\eta}\left\{[1+v(\mu-1)(2-v)]\frac{(2-v)(1-v)+(\mu-1)[v(1-v)+2v(2-v)]}{(1-v)^2[1+2v(\mu-1)(2-v)]} - 1\right\} \tag{A11}$$

From equation (45), it can be shown that the component $\frac{(2-v)(1-v)}{(1-v)^2}$ $\frac{+(\mu-1)[v(1-v)+2v(2-v)]}{[1+2v(\mu-1)(2-v)]}$ is positive and greater than one for all feasible v,

and that $[1+v(\mu\text{-}1)(2\text{-}v)]$ is also positive and greater than one. Therefore, the term $[1+v(\mu-1)(2-v)]\frac{(2-v)(1-v)+(\mu-1)[v(1-v)+2v(2-v)]}{(1-v)^2[1+2v(\mu-1)(2-v)]}$ is positive and greater than one. Henceforth, from equation (30), it is $\frac{dR_s}{dF_s}>0$.

Proof of proposition 4:

We define the firm's revenue, given demand; described by equation (31) as

$$h^{'}m^{'} = h^{'1-\mu}\frac{\eta F}{Nh^{1-\mu}}\{\xi^{1-\mu}[R_s-1)\eta+1]+\xi^{\mu-1}\} \tag{A12}$$

The firm chooses to maximize $h^{'}$ using as a profit function:

$$z^{'} = h^{'}m^{'}-r^{'}m(F_s,L) \tag{A13}$$

We aim to prove that proposition 4 holds by contradiction. So, by differentiation we get the profit maximizing price. Setting profits equal to zero and substituting in for h' from equation (32) and for m' from equation (31) in equation (A13), we have

$$r^{'-\eta}\left(\frac{\rho\eta}{\eta-1}\right)^{1-\eta}\frac{\sigma(\eta-1)}{\rho}\frac{nF\{\xi^{1-\mu}[R_s-1)\overset{\leftrightarrow}{\eta}+1]+\xi^{\mu-1}\}}{Nh^{1-\mu}}-\sigma-\rho\left(\frac{\rho\mu}{\mu-1}\right)^{-\mu}r^{'-\eta}$$
$$\frac{nF\{\xi^{1-\mu}[R_s-1)\overset{\leftrightarrow}{\eta}+1]+\xi^{\mu-1}\}}{Nh^{1-\mu}} = 0 \tag{A14}$$

Solving for r', we get the zero profit return as in equation (33). To prove that equation (34) is not satisfied at $\xi = 1$, recall that

$$2[R_s-1)\overset{\leftrightarrow}{\eta}+1] = \frac{2R_s}{\eta} \tag{A15}$$

Denote the zero profit return at $\xi=1$ by r' (1). Using equation (33) and that K S/ v we have that

$$r^{'}(1) = \frac{\eta-1}{\rho\eta}\left[\frac{\sigma(\eta-1)}{\rho}\frac{(Nh^{1-\mu})/v}{4nFR_s}\right]^{-\frac{1}{\eta}} \tag{A16}$$

Using equilibrium h in equation (22), equation (A16) is written as

$$r'(1) = R_s v^{-\frac{1}{\mu}}(1-v)^{\frac{2(1-\mu)}{\mu}}\left(1-\frac{v}{2}\right)^{\frac{1-\mu}{\mu}}\left[\frac{\sigma\mu S}{2\overleftrightarrow{\eta}F}\right]^{-\frac{1}{\eta}} \tag{A17}$$

Recall that $2\overleftrightarrow{\eta}F=F_S$ and from equation (21) we have that

$$\frac{\sigma\mu S}{F_s} = v\left(1-\frac{v}{2}\right)\left[(\mu-1)v\left(1-\frac{v}{2}\right)-1\right] \tag{A18}$$

Substituting equation (A17) into equation (51) we get

$$r'(1) = R_s\left[2(\mu-1)v\left(1-\frac{v}{2}\right)+1\right]^{-\frac{1}{\mu}}\left(1-\frac{v}{2}\right)^{-1}(1-v)^{\frac{2(1-\mu)}{\mu}} \tag{A19}$$

Consequently, the free trade equilibrium is not sustainable (from equation (34)) if it holds the following inequality

$$\left[2(\mu-1)v\left(1-\frac{v}{2}\right)+1\right]^{-\frac{1}{\mu}}(1-v)^{\frac{2(1-\mu)}{\mu}} \geq \frac{1-\frac{v}{2}}{1-\frac{S}{2}} \tag{A20}$$

Inequality (A20) does not hold since at v=0, the first derivative (slope) of left-hand side is 0, but the right-hand side is above unity.