A Spatial Theory of Trade

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The equilibrium relationship between trade and the spatial distribution of economic activity is fundamental to the analysis of national and regional trade patterns, as well as to the effect of trade frictions. We study this relationship using a trade model with a continuum of regions, transport costs, and agglomeration effects caused by production externalities. We analyze the equilibrium specialization and trade patterns for different levels of transport costs and externality parameters. Understanding trade via the distribution of economic activity in space naturally rationalizes the evidence on border effects and the "gravity equation." (*JEL* F1, R0, R3)

Trade is spatial by nature. The distribution of economic activity in space determines the pattern of trade across and within countries. Conversely, trade allows firms in a region to specialize in the production of a small number of goods, while consumers and firms demand a much larger basket of products. Casual observation of the pattern of spatial specialization and employment concentration is enough to realize that the distribution of economic activity in space is not perfectly concentrated or uniform. Hence, theories that imply a realistic distribution of economic activity need to introduce the benefits and costs from spatial specialization, namely, agglomeration and congestion forces. The benefits that firms in a particular location may derive from locating near firms in the same sector have to compensate for the extra costs of exporting production and importing intermediate inputs. This trade-off results in a variety of possible spatial patterns of production and trade flows that we study in this paper.

The *necessary* agglomeration and congestion forces lead to a spatial trade theory that can rationalize empirical observations that may seem hard to explain with standard trade arguments. One example is the effect of national borders on trade. The empirical literature has found that national borders reduce international trade flows and increase regional trade flows substantially.[1] What allows borders to have this important effect on trade flows and specialization patterns? Transport costs are ruled out, given that national borders matter even after controlling for distance. Other trade costs, like import taxes, would require either unreasonably high costs, or very high elasticities of trade with respect to these barriers. Clearly, high tariffs cannot account for the observed border effects of the European Union or North America.[2] What about a high elasticity of trade with respect to tariffs? The theory in this paper naturally delivers this high elasticity. The idea is that tariffs imply a discontinuity in relative prices at borders, which changes specialization patterns. Agglomeration effects and transport costs amplify this effect in equilibrium—the first, since new or bigger clusters of firms affect the productivity of nearby firms, the second, since these new clusters supply goods mostly for the domestic market, consequently reducing international and increasing regional trade.[3]

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[1] See John McCallum (1995), Shang-Jin Wei (1996), John F. Helliwell (1998), and James E. Anderson and Eric van Wincoop (2003). See also Holger C. Wolf (2000) and Thomas J. Holmes (1998) for the importance of state borders.

[2] Notice, however, that such other barriers as different legal systems, languages, or currencies may have similar effects as deliberate trade policy.

[3] See Daniel Trefler (2004) for evidence on effective U.S.-Canada trade tariffs. Helliwell (1998) and Charles Engel and John H. Rogers (1996) provide some evidence that border effects are important for relative prices. See

Our theory provides a new angle to look at other related questions in trade. Empirical studies that use the gravity equation have shown that trade flows decrease with distance: a direct implication of the necessary congestion force.[4] Furthermore, a spatial framework is necessary for transport costs and trade frictions to have distinct effects on trade patterns and the volume of trade.[5] Another immediate implication of a spatial setup is that relative prices of intermediate goods are higher in countries that import these goods, as in the data.[6] More generally, our theory can address questions on how trade barriers, transport costs, and technology affect the distribution of economic activity in space, and the corresponding trade flows.

The international trade literature has paid little attention to space. Paul Krugman (1991b) pointed this out and presented a model of trade between two regions. Following the publication of his paper, several studies have tried to model space and to demonstrate how space, via transport costs, can explain several puzzles in international economics.[7] In virtually all papers in this literature, regions are modeled as points in space, land is not an input in production, and firms can locate only in one area, or a small number of areas, within a country. One noteworthy exception is Krugman and Venables (1995b). The paper presents a model of spatial specialization between manufacturing and agricultural sectors with a continuum of locations. It assumes, however, that factors are geographically immobile. International barriers on migration are important and we will consider them, but we relax the assumption of no regional or local mobility of labor. Even more important, Krugman and Venables (1995b) do not study the effect of trade frictions.

Eaton and Kortum (2002) have written another paper in this tradition, although with a discrete number of locations. They present a Ricardian model of trade with geographic barriers which is successful in replicating the volume and pattern of trade. The paper assumes that Total Factor Productivity (TFP) levels in each industry are random realizations from a distribution with country-specific mean and common variance. What determines the distribution of TFP? Our view of trade implies that the agglomeration of firms in an industry at a geographic location—the pattern of geographic specialization—is jointly determined in equilibrium with the distribution of measured TFP.

We build a spatial model of trade that considers a continuum of regions in a line. To do this we rely on two literatures: the Ricardian trade literature (as in Rudiger Dornbusch et al., 1977), and the urban literature (as in Robert E. Lucas, Jr. and Rossi-Hansberg, 2002). The model can be seen as a spatial Ricardian model of comparative advantage where technological differences are endogenous and determined by spatial specialization patterns through production externalities.

The remainder of the paper is organized as follows. We set out the model in Section I and discuss the construction of an equilibrium in Section II. In Section III, we characterize the equilibrium and prove results related to the magnitude of relative prices across regions and the effect of distance on trade flows. Section IV introduces trade barriers and discusses their effect on trade flows. Up to this point, the paper assumes perfect labor mobility; in Section V we relax this assumption and in Section VI we present several numerical simulations of the model. Section VII concludes.

I. The Model

The spatial structure is a line from $-S$ to S, where $-S$ and S represent the northern and southern borders of the region under study. The sum of the length of all countries is $2S$. The density of land at each point in the line is equal to one. Throughout the paper, we refer to a location as a point in the line and to a region as an interval with positive length. Countries are ordered sequentially and are connected intervals

Kei-Mu Yi (2003, 2005) for other theoretical explanations.

[4] See, for example, Jeffrey H. Bergstrand (1989), Marcos Sanso et al. (1993), Peter Egger (1999), and Simon J. Evenett and Wolfgang Keller (1998).

[5] This assumes that we set aside general equilibrium effects resulting from the possible uses of tax revenue.

[6] See, for example, Jonathan Eaton and Samuel Kortum (2002) for empirical evidence.

[7] Some examples are Maurice Obstfeld and Kenneth Rogoff (2000), Eaton and Kortum (2002), David Hummels (1999), Diego Puga and Anthony J. Venables (1996, 1997), Krugman and Venables (1995a), and Krugman (1991a, 1994, 1995). Donald Davis and David Weinstein (2003) have shown empirically the presence and importance of the type of home market effects that arise in spatial theories.

in the line. For what follows in this section, we assume that there are no restrictions to trade or to the flow of labor. Hence, for the moment, the specific location of borders is irrelevant. In following sections, we analyze cases with these types of restrictions.

There are two goods, a final good (FG) and an intermediate good (IG). Agents consume the FG only. The FG is produced using land, labor, and the IG. Production of the FG per unit of land at some location $r \in [-S, S]$ is given by

$$x^F(r) = g^F(z^F(r))f^F(n^F(r), c^I(r))$$

where $n^F(r)$ is the number of workers per unit of land specialized in the production of FGs at r (from now on the density of workers at r); $c^I(r)$ the demand for the IG per unit of land specialized in the FG sector at r; and $z^F(r)$ a production externality that depends on how many workers are employed at all locations in the FG sector.

The IG is produced using land and labor. Production per unit of land of the IG at r is given by

$$x^I(r) = g^I(z^I(r))f^I(n^I(r))$$

where $n^I(r)$ is the density of workers in this sector at r and $z^I(r)$ the sector-specific production externality. Let γ^i denote the elasticity of g^i with respect to z^i, $i = I, F$.

The external effect in a sector depends on the number of workers employed in the same sector at each location. It is supposed to be linear and to decay exponentially with distance at rate δ^F for the FG sector and δ^I for the IG sector.[8] Hence, in the FG sector,

$$z^F(r) = \int_{-S}^{S} \delta^F e^{-\delta^F|r-s|} n^F(s)\theta(s)\, ds$$

where $\theta(r)$ is the proportion of land used for FG production at r. So $1 \geq \theta(r) \geq 0$ for all $r \in [-S, S]$. For the IG, the external effect is calculated similarly,

$$z^I(r) = \int_{-S}^{S} \delta^I e^{-\delta^I|r-s|} n^I(s)(1-\theta(s))\, ds.$$

Agents consume only the FG; they do not consume land or the IG. The utility of an agent living and working at r is given by $U(c^F(r))$ where $c^F(r)$ denotes consumption of the FG at r. There is a perfectly elastic supply of workers at utility $\bar{u}$, so agents live and work at location r if $U(c^F(r)) \geq \bar{u}$. That is, there is free mobility of labor across regions, so the utility of each worker is the same regardless of her location. This implies that $c^F(r) = \bar{c}^F \equiv U^{-1}(\bar{u})$, assuming that U is a strictly increasing function.

It is costly to transport goods between locations.[9] If one unit of good i is transported from r to s, only a fraction

$$e^{-\kappa^i|r-s|}, \quad i = F, I,$$

reaches s. Namely, we assume iceberg transport costs where κ^i is the transport cost per unit of distance in industry i. We assume throughout the paper that κ^i is positive and finite.

Let $p^F(r)$ and $p^I(r)$ be the price of FGs and IGs, respectively, at r. Then, an agent's wage at r must be given by $w^F(r) = p^F(r)\bar{c}^F$ and $w^F(r) = w^I(r) \equiv w(r)$, where the first equation is the agent's budget constraint and the second results from free mobility across sectors. Thus, wages are proportional to the price of FGs, and real wages are constant at $\bar{c}^F$.

Landlords are assumed to consume what they earn from land rents at the location where they live, and they consume FGs only. In FG regions, landlords consume part of the production. In IG regions, landlords consume part of the imports of FGs. Landlords do not work.

The maximization problem of a firm that produces the IG at location r is given by

$$(1) \qquad \max_n \; p^I(r)g^I(z^I(r))f^I(n) - w(r)n.$$

[8] Masahisa Fujita and Jacques-François Thisse (2002) show how this particular specification of external effects can be justified as knowledge spillovers. If the production of ideas requires the interaction between people working in different firms at different locations, the closer other producers are, the more ideas generated and, hence, the more productive firms in that region. Guy Dumais et al. (2002), J. Vernon Henderson (1988), Frank Pyke et al. (1990), and Annalee Saxenian (1994) provide evidence of this type of externalities at the regional level.

[9] See Hummels (1999) and Anderson and van Wincoop (2004) for empirical evidence on transport costs.

The first-order condition with respect to n is

$$p^I(r)g^I(z^I(r))f^I_{n^I}(n^I(r)) = w(r) = p^F(r)\bar{c}^F.$$

Denote the relative price of IGs by $p(r) \equiv p^I(r)/p^F(r)$; then, the first-order conditions define the density of workers in the IG sector ($\hat{n}^I(p(r), z^I(r)) = n^I(r)$) as a function of the relative price of the IG and productivity, $z^I(r)$.

The production of the IG at location r is competitive, so firms take all prices as given and earn zero profits. Maximized output minus labor costs (in units of FGs) is then the land bid rent of IGs firms ($R^I(r)$),

$$R^I(r) = p(r)g^I(z^I(r))f^I(n^I(r)) - \bar{c}^F n^I(r).$$

Similarly, the maximization problem of firms in the FG sector at r is

$$\max_{n,c} p^F(r)g^F(z^F(r))f^F(n, c) - w(r)n - p^I(r)c. \tag{2}$$

So the first-order conditions are

$$g^F(z^F(r))f^F_n(n^F(r), c^I(r)) = \bar{c}^F$$

and

$$g^F(z^F(r))f^F_c(n^F(r), c^I(r)) = p(r).$$

These conditions define $\hat{n}^F(p(r), z^F(r)) = n^F(r)$ and $\hat{c}^I(p(r), z^F(r)) = c^I(r)$ as the density of workers in the FG sector and the demand of the IG as a function of the relative price of the IG and productivity $z^I(r)$. Notice that the marginal product of labor in the FG sector is constant across locations, since real wages are constant. Again, the FG industry is supposed to be competitive at all locations and so firms earn zero profit. The land bid rent of FG firms ($R^F(r)$) is given by

$$R^F(r) = g^F(z^F(r))f^F(n^F(r), c^I(r)) - \bar{c}^F n^F(r) - p(r)c^I(r).$$

In order to impose equilibrium conditions in both goods markets, we need to keep track of the number of goods produced in each region, the amount of goods traded, and the number of goods lost in transportation. Since the pattern of trade across locations is endogenous, and potentially complicated, it is difficult to define a standard equilibrium condition. The following formulation allows us to impose equilibrium conditions in a simple way. Let $H^F(r)$ be the excess supply of the FG accumulated between $-S$ and r, once all the relevant trades in $[-S, r]$ have been taken into account and goods have been transported to location r. Then, by definition, $H^F(-S) = 0$ and in order for the excess supply in the world to equal zero—equilibrium in the FG market—we need $H^F(S) = 0$. The evolution of this stock is dictated by the following differential equation:

$$\frac{\partial H^F(r)}{\partial r} = \theta(r)[x^F(r) - \bar{c}^F n^F - R^F(r)] - (1 - \theta(r))[\bar{c}^F n^I(r) + R^I(r)] - \kappa^F|H^F(r)|.$$

At each location r, we add to the stock of excess supply the total production minus total consumption of the FG in the FG sector, $\theta(r)[x^F(r) - \bar{c}^F n^F - R^F(r)]$, and we subtract total consumption of the FG in the IG sector, $(1 - \theta(r))[\bar{c}^F n^I(r) + R^I(r)]$. We then need to take into account that, if $H^F(r)$ is positive, as we increase r we need to transport FGs farther away from where they are produced. A fraction κ^F of these goods is destroyed during transportation, so we need to reduce the accumulated excess supply accordingly. If $H^F(r)$ is negative the intuition is similar.

Using the definition of $R^F(r)$ and $R^I(r)$—the consumer's budget constraint and the firm's zero profit condition—we can simplify the equation to get

$$\frac{\partial H^F(r)}{\partial r} = p(r)[\theta(r)c^I(r) - (1 - \theta(r))x^I(r)] - \kappa^F|H^F(r)|. \tag{3}$$

The construction of $H^I(r)$ parallels the one of $H^F(r)$, so

$$\frac{\partial H^I(r)}{\partial r} = (1 - \theta(r))x^I(r) - \theta(r)c^I(r) - \kappa^I|H^I(r)|. \tag{4}$$

At each location r, we add the total production of IGs, $(1 - \theta(r))x^I(r)$, subtract the number of IGs used for production in FGs sectors, $\theta(r)c^I(r)$, and adjust for extra transport costs, $-\kappa^I|H^I(r)|$.

The balanced trade condition at each location, $r \in [-S, S]$, is then given by

$$H^F(r) + p(r)H^I(r) = 0. \tag{5}$$

That is, the sum of excess supplies, expressed in terms of FGs, is zero at each location.[10] The expression takes into account goods consumed and produced at all locations, but also the loss of some of these goods in transportation. An immediate implication is that for $p(r) > 0$, $H^F(r) = 0$ is equivalent to $H^I(r) = 0$. So $H^F(S) = 0$ implies $H^I(S) = 0$: Walras's Law.

Competition for land implies that land is assigned to its highest value. Namely,

(6) $R^F(r) > R^I(r)$ implies $\theta(r) = 1$,

(7) $R^F(r) = R^I(r)$ implies $\theta(r) \in (0, 1)$, and

(8) $R^F(r) < R^I(r)$ implies $\theta(r) = 0$.

Given z^F and z^I, the Envelope Theorem implies that

$$\frac{\partial R^I(r)}{\partial p(r)} = g^I(z^I(r))f^I(n^I(r)) > 0,$$

and

$$\frac{\partial R^F(r)}{\partial p(r)} = -c^I(r) < 0,$$

for all $r \in [-S, S]$. Define the mixed relative price p_m as the relative price that equalizes the value of land in both sectors. Given our assumptions, p_m is well defined and unique. The mixed relative price, $p_m(r)$, depends on r only through the productivity functions. Hence, (6) to (8) can be restated as

(9) $p(r) < p_m(r)$ implies $\theta(r) = 1$,

(10) $p(r) = p_m(r)$ implies $\theta(r) \in (0, 1)$, and

(11) $p(r) > p_m(r)$ implies $\theta(r) = 0$.

So if, for example, the relative price of IGs at r is higher than a certain threshold, $p_m(r)$, land is more valuable if used in the production of IGs.

In equilibrium, agents buy goods from the location with the lowest price after transport costs. This implies that prices across locations have to satisfy a no-arbitrage condition. Suppose that a firm located at r is shipping IGs to location s. Then, by no arbitrage, it has to be the case that

$$p^I(r) = e^{-\kappa^I|r-s|}p^I(s).$$

Suppose that the condition is not satisfied, since $p^I(r) > e^{-\kappa^I|r-s|}p^I(s)$. Then, IG firms prefer to sell their goods at location r rather than at location s. This, however, contradicts our original assumption that firms located at r were shipping IGs to location s. Suppose conversely that $p^I(r) < e^{-\kappa^I|r-s|}p^I(s)$. Then, agents could buy the good at location r, transport it themselves, and get the good at s at cost $e^{\kappa^I|r-s|}p^I(r)$. They could then sell the good at location s making a profit: an arbitrage. Hence, the condition above has to be satisfied *if* IGs are being transported from r to s. The same is true for FGs: *if* FGs are being transported from r to s, no arbitrage implies that

$$p^F(r) = e^{-\kappa^F|r-s|}p^F(s).$$

If goods produced at r are being shipped to location s, $|H^F(r')| > 0$ for all $r' \in [r, s]$. The reason is that, if $H^F(r') = 0$ at some location r' in between r and s, after accounting for all trades in region $[-S, r']$, the excess supply of the FG is zero. This means that no goods are being traded between $[-S, r']$ and $[r', S]$, which contradicts the original assumption that r was trading with s. Hence, we can divide the original interval $[-S, S]$ into different regions with boundaries defined by locations r where $H^F(r) = 0$. There is trade within these regions, but no trade across them.

Balanced trade implies that if a region exports IGs, it has to import FGs. If r exports IGs

[10] The balanced trade condition can also be expressed only in terms of local production and consumption as $\partial H^F(r)/\partial r + p(r)\partial H^I(r)/\partial r + (\kappa^I + \kappa^F)p(r)|H^I(r)| = 0$.

to s, s exports FGs to r.[11] This can happen via trades with some locations in between r and s, or directly. Hence, if the net flow of IGs from r to s is positive, $H^F(r') < 0$ for all $r' \in [r, s]$,

$$p(r) = e^{-(\kappa^I + \kappa^F)|r-s|}p(s). \tag{12}$$

If the net flow of FGs from r to s is positive, $H^F(r') > 0$ for all $r' \in [r, s]$,

$$p(r) = e^{(\kappa^I + \kappa^F)|r-s|}p(s). \tag{13}$$

If location r is a mixed area—an area where both goods are produced—it has to be the case that no goods are shipped from or to location r. The reason is that, if not, prices would have to satisfy (12) or (13) together with

$$p(r) = p_m(r).$$

This can happen but only at a point in space: a transversal crossing. Hence, in mixed areas, prices are given by p_m and $H^F(r) = H^I(r) = 0$ so

$$(1 - \theta(r))x^I(r) = \theta(r)c^I(r).$$

We still need to guarantee that it is not beneficial for other locations in the mixed area to buy goods from, or sell goods to, location r. So when $\theta(r) \in (0, 1)$, prices have to satisfy

$$e^{(\kappa^I + \kappa^F)|r-s|}p(s) \geq p(r) \geq e^{-(\kappa^I + \kappa^F)|r-s|}p(s). \tag{14}$$

The condition guarantees that in mixed areas prices do not compensate for transport costs, and so in equilibrium these areas do not trade.

Let M_+ be the space of nonnegative and continuous functions. For the definition of equilibrium, it is useful to define two operators, $T^F : M_+ \times M_+ \to M_+$ and $T^I : M_+ \times M_+ \to M_+$ by

$$T^F(z^F, z^I)(r) \equiv \int_{-S}^{S} \delta^F e^{-\delta^F|r-s|}n^F(s; z^F, z^I)\theta(s; z^F, z^I)\, ds,$$

and

$$T^I(z^F, z^I)(r) \equiv \int_{-S}^{S} \delta^I e^{-\delta^I|r-s|}n^I(s; z^F, z^I) \times (1 - \theta(s; z^F, z^I))\, ds.$$

Notice that we are stressing in the notation that n^F, n^I, and θ are functions of both productivity functions z^F and z^I. In equilibrium, the employment densities that result from a pair of productivity functions have to produce externalities that result in the productivity levels implied by these operators. That is, an equilibrium allocation is a fixed point of these operators.

We are ready to define an equilibrium in this economy.

DEFINITION: *An equilibrium is a set of functions* $\{n^F, n^I, c^F, c^I, z^F, z^I, H^F, H^I, p, R^I, R^F, \theta\}$ *such that*

(*i*) *In all locations* $r \in [-S, S]$, $U(c^F(r)) = \bar{u}$.
(*ii*) *Firms solve problems* (1) *and* (2).
(*iii*) *Agents and firms buy goods from locations with the lowest price after transport costs: the no-arbitrage conditions* (12), (13), *and* (14) *are satisfied.*
(*iv*) *Land is assigned to its highest value, so conditions* (6) *to* (8) *are satisfied.*
(*v*) H^F *and* H^I *evolve according to equations* (3) *and* (4),

$$H^F(-S) = H^I(-S) = H^F(S) = H^I(S) = 0$$

and, for all $r \in [-S, S]$, *the trade balance condition is satisfied:*

$$H^F(r) + p(r)H^I(r) = 0.$$

(*vi*) *For all* $r \in [-S, S]$,

$$T^F(z^F, z^I)(r) = z^F(r) \text{ and}$$

$$T^I(z^F, z^I)(r) = z^I(r).$$

II. Construction and Existence of an Equilibrium

The construction of an equilibrium in this setup falls naturally into two steps. The first step is to find an allocation that satisfies conditions (i) to (v) in the definition of equilibrium, given the

[11] This implication holds only in a two-industry setup.

productivity functions (z^F, z^I). The second step is to find a pair of functions (z^F, z^I) such that condition (vi) is satisfied.

Given a pair of productivity functions (z^F, z^I), an allocation is uniquely determined by a relative price path p. Let $p(r, \pi)$ be the relative price at location r associated with a price path starting at $\pi, p(-S, \pi) = \pi$. At any location r, as we increase r (move to the south), the relative price path has to grow at rate $(\kappa^F + \kappa^I)$ if $H^F(r) < 0$; decline at rate $(\kappa^F + \kappa^I)$ if $H^F(r) > 0$; either grow (if $p(r) \geq p_m(r)$) or decline (if $p(r) \leq p_m(r)$) at rate $(\kappa^F + \kappa^I)$; or follow $p(r) = p_m(r)$ if $H^F(r) = 0$. To construct an equilibrium relative price path, we can start with an initial relative price, π, and follow these rules to obtain a candidate equilibrium relative price path. Since every time $H^F(r) = 0$ and $p(r) = p_m(r)$ the relative price path can evolve in three different ways, there may be many relative price paths associated with an initial relative price. Hence, each initial relative price path may be associated with many final stocks of excess supply of the FG,

$$\varphi^F(\pi) \equiv H^F(S, \pi).$$

That is, $\varphi^F(\pi)$ is a correspondence. We are looking for a π such that $0 \in \varphi^F(\pi)$. Numerically, we can do this using a shooting algorithm, since $H^F(S, \pi)$ is decreasing in π under the assumptions we impose below. We then need to find a fixed point of the operators T^F and T^I, which for γ^i small enough, have iterates that converge.

Proposition 1 guarantees that there exists such a π and an associated price path so that the first five equilibrium conditions are satisfied. Proposition 2 uses Schauder's fixed-point theorem to prove that there exists a pair of functions (z^F, z^I) that satisfy condition (iv). Many of the arguments in the proofs of the theorems parallel the arguments in Lucas and Rossi-Hansberg (2001) (the actual proofs can be found in Rossi-Hansberg, 2003). The existence theorems are proven using the following assumptions.

ASSUMPTION A:

(*i*) *Both g^F and g^I are continuously differentiable and concave.*
(*ii*) *f^F is continuously differentiable, strictly increasing in both arguments, strictly concave, and f_n^F (the marginal product of labor) is strictly increasing in c^I.*
(*iii*) *f^I is continuously differentiable, strictly increasing, and strictly concave.*
(*iv*) *There exists a pair of constants $0 < \underline{\varepsilon} < \bar{\varepsilon} < \infty$ such that for any $x \in \mathbb{R}_+$*

$$\bar{\varepsilon} \geq g^F(x) \geq \underline{\varepsilon}$$

and

$$\bar{\varepsilon} \geq g^I(x) \geq \underline{\varepsilon}.$$

(*v*) *g^F, g^I, f^F, and f^I satisfy, for all $c^I \in \mathbb{R}_+$,*

$$\lim_{x\to\infty} \frac{\partial g^F(x) f^F(x, c^I)}{\partial x} = \lim_{x\to\infty} \frac{\partial g^I(x) f^I(x)}{\partial x} = 0.$$

(*vi*) *U is strictly increasing and strictly concave.*

Part (iii) of Assumption A implies that when the relative price of IGs increases, the density of employment in the FG sector decreases. Part (iv) of Assumption A guarantees that the productivity of any firm is positive, and that even if the external effect is infinitely large, the productivity of firms is bounded. The magnitude of these bounds is arbitrary.

PROPOSITION 1: *Under Assumption A, for any pair of positive and continuous productivity functions z^F and z^I there is an allocation that satisfies conditions (i) to (v). Any such allocation is associated with a uniquely determined relative price path $p(r)$. Except for intervals on which $p(r)$ coincides with the mixed path and with either* (12) *or* (13), *the allocation is uniquely determined.*

PROOF:
See Rossi-Hansberg (2003).

PROPOSITION 2: *Under Assumption A, there exists an equilibrium allocation. That is, there exists a pair of functions (z^F, z^I) such that $T^F(z^F, z^I)(r) = z^F(r)$ and $T^I(z^F, z^I)(r) = z^I(r)$.*

PROOF:
See Rossi-Hansberg (2003).

The model can be seen as a Ricardian model of comparative advantage if we define equilibrium only by conditions (i) to (v), given z^I and z^F. In this case, the productivity of each sector at each location is given exogenously and we can determine the optimal distribution of production activities. This would be the case if, for example, natural resources determine the productivity of regions in both industries. Once we add condition (vi), the equilibrium allocation cannot be proven to be unique. This implies that the initial productivity functions—used as a starting point in the algorithm to construct an equilibrium—determine the equilibrium that is reached. One interpretation of this dependence is that history matters. Location of firms in different sectors and their productivity at some point in time determine the equilibrium allocation in the future.

The potential multiplicity of equilibria in this setup is limited by the presence of the endpoints $-S$ and S. Since there is no production beyond these points, locations at these boundaries tend to have lower productivity. We could, instead, think about the distribution of economic activity in a circle where these endpoint effects are not present. In a circular world, we need to analyze equilibria up to a rotation, given the lack of geography. If spillovers decline fast enough with distance so the effect of the endpoints on productivity is small, the role of endpoints is almost entirely to select one allocation out of the continuum of identical equilibria in the circular world. One can show numerically that this is the case for the examples in Section VI. Note that in a world without endpoints, as in the circular spatial setup, it is impossible to think about countries that are isolated because of their geography. The United States and Argentina would have the same spatial characteristics. In a world with geography, and therefore with endpoints as in our setup, we can think about the location of countries in the world.

III. Characterization of an Equilibrium

In order for an allocation to be an equilibrium, prices have to satisfy the no-arbitrage conditions and land has to be assigned to its highest value. From these two properties we can construct a graph that is helpful in understanding how land is assigned to its different uses. Given the productivity functions, we can calculate p_m for all locations. Equations (9) to (11) imply that if the relative price of IGs is above p_m, the region produces IGs, so $\theta = 0$. If the relative price is below p_m, the area produces FGs, $\theta = 1$, and if it is equal, it produces both goods, $\theta \in (0, 1)$. We also know from (12) to (14) that, as r increases, the relative price function has to grow at rate $-(\kappa^F + \kappa^I)$, $(\kappa^F + \kappa^I)$, or be equal to p_m. Given a relative price at $-S$, we can construct a relative price function using the rules above. Proposition 1 guarantees that there is a unique relative price at $-S$ that satisfies the goods market equilibrium conditions (v). At locations where $H^F(r) = H^I(r) = 0$, there is a kink in the relative price function. The reason is that shipments of goods change direction at 0. The construction is illustrated in Figure 1 if we focus on the curves marked p and p_m only. At $-S$, $p(-S) > p_m(-S)$ so the region close to the left boundary sells IGs and the price function grows with r. When p crosses p_m, we switch to an FG-producing region. At $r = 0$, $H^F(0) = 0$ and so the flow of goods changes direction, which implies a kink in the price function that now decreases with r.

In this construction, relative prices of IGs are higher in FG-producing regions than in adjacent IG-producing regions. This confirms our claim that the model is consistent with high capital goods prices in developing countries. Relative prices of IGs may be low or high in regions that produce both goods. We formalize the result in the following proposition; the proof is included in the Appendix.

PROPOSITION 3: *The relative price of IGs is higher in regions such that $\theta = 1$ than in adjacent regions such that $\theta = 0$.*

Since prices adjust according to transport costs, firms in a particular location are indifferent about trading with several partners. That is, prices adjust to compensate for transport costs in regions such that H^F does not change sign (FGs are being shipped in one direction only). If $H^F(r) = 0$, there is no trade between locations $r' < r$ and locations $r'' > r$. We need a definition of bilateral trade that is consistent with this characteristic of the model. If goods are being shipped between two locations, we can think about all locations in between them as importing the shipment, adding their own exports or taking out their imports, and shipping the remaining goods further. We can then define trade between two locations as the minimum (because of trade balance) of the flow of goods that passes through each of them. Formally, define trade between two locations r and s, where $r > s$, as

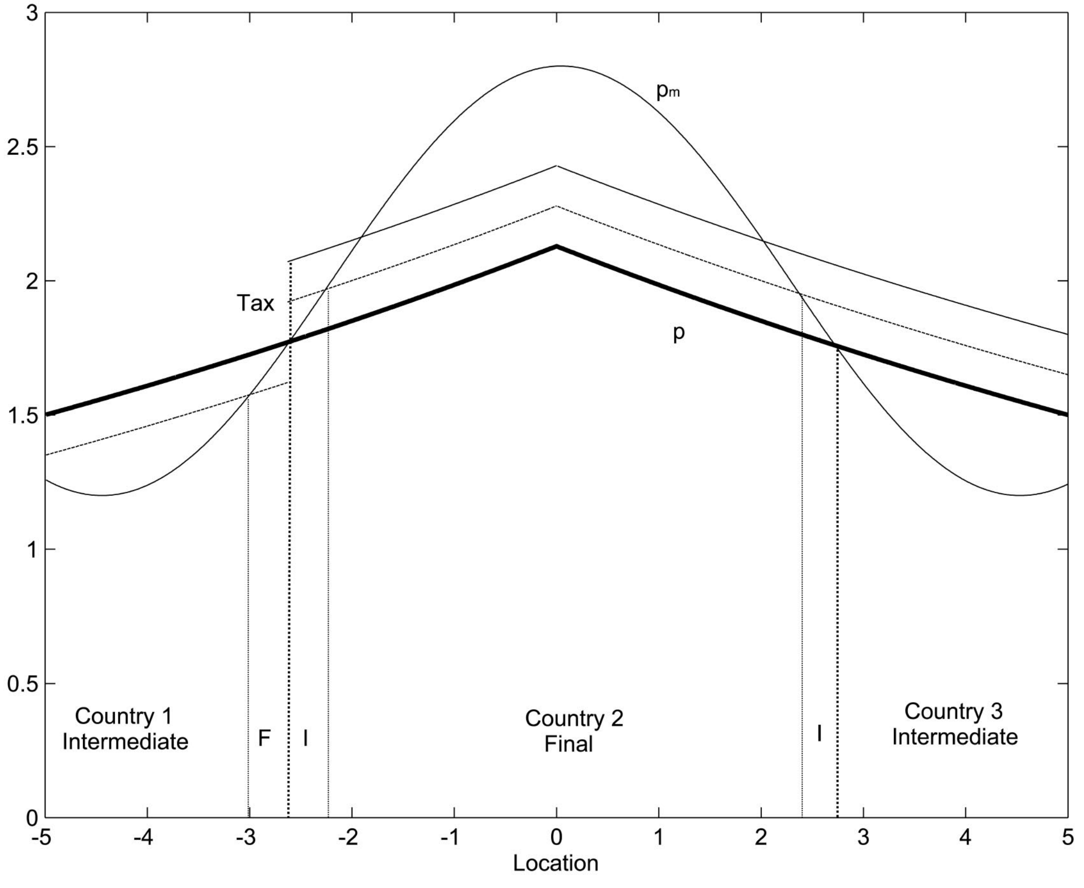

FIGURE 1. THE EFFECT OF AN IMPORT TAX WITH FIXED PRODUCTIVITIES

$$Tr(r, s) = \begin{cases} \min\{|H^F(r)|, |H^F(s)|\} \\ \quad \text{if } |H^F(r')| > 0 \ \forall r' \in (r, s) \\ 0 \text{ otherwise.} \end{cases}$$

With this definition at hand, we can show that distance reduces bilateral trade.

PROPOSITION 4: *If two locations produce different goods, the closer they are, the more they trade.*

An equilibrium in this economy exhibits other properties that are worth mentioning:

- The equilibrium allocation depends only on the sum of transport costs $\kappa^F + \kappa^I$: it is evident that only the sum matters in the construction of the equilibrium price path. Using trade balance, it is easy to write the equilibrium conditions as a function of the sum of transport costs only.
- Given the productivity functions, higher transport costs imply more regions in autarky: higher transport costs increase the absolute value of the slope of the price function, which then crosses the mixed relative price curve more often.
- As transport costs go to infinity, all locations are in autarky and prices and production are determined only by productivity functions.
- As transport costs go to zero, the price function is constant and at least one good is produced in only one region.
- As the land share in production goes to zero in one sector, the sector concentrates in one region and the size of the region decreases with $\bar{\varepsilon}$.

IV. Trade Barriers

Thus far, we have described a world without frictions in which agents and firms are freely mobile, and so national borders do not play a role. In this section, we give countries the possibility to levy taxes on the imports and exports of goods, and analyze the equilibrium implications of trade policy. Assume that a country that exports FGs decides to impose a tax on the imports of IGs from a particular country. Suppose, for example, that this country occupies locations $[s_2, s_3]$, and that the country from which it imports IGs occupies locations $[s_1, s_2]$. Then, the relative price of IGs has to satisfy

$$p(r) = e^{(\kappa^I + \kappa^F)|r-s|}p(s) + \tau$$

for $r \in (s_2, s_3]$ and $s \in [s_1, s_2)$, where τ is the tax per unit of the IG. Other types of tariffs can be introduced in an analogous way. The result of such a policy is that the country that exports FGs produces more IGs, and the other country produces more FGs. This is a spatial version of the standard effect of tariffs. In contrast with standard theories, however, this setup allows us to analyze what happens with prices and the location of production activity within both countries when the tax is imposed.

Figure 1 illustrates the example, given productivity functions. Country 2, specializing in FGs, imposes a tax on the imports from Country 1. The solid line is the relative price of IGs without taxes. Once the tax is imposed, the relative price of IGs in Country 2 goes up at the border. This is illustrated by the solid thin line in the figure. The tax prompts some locations in Country 2 to switch and produce the IG instead of the FG. This allocation cannot be an equilibrium, since at these prices the world produces too many IGs. There is an excess supply of IGs, which leads to a decrease in the relative price of IGs at all locations. The resulting relative price is the dashed line. Notice that because of the decrease in the price of IGs, some locations in Country 1 start producing FGs.

This example stresses two implications of the model. First, transport costs and trade barriers have very different effects on the equilibrium allocation. Without trade barriers, the relative price function is continuous. Different transport costs imply a different evolution of the relative price function, but no discontinuities. If, instead of having a continuum of regions we had considered several points in space (as most of the previous literature), we could not make this distinction, so by assumption, as Obstfeld and Rogoff (2000) point out, the model would imply that tariffs and transport costs have exactly the same effect. Second, trade barriers reduce trade, as expected, and increase the set of goods that each country produces. Once we allow the productivity function to adjust, these effects on trade flows are even larger. Producing the FG in Country 1 makes this country better at producing FGs. Trade policy affects the productivity at which different goods are produced by changing the distribution of economic activity in space.

In the next Proposition, we formalize the effect of trade barriers given productivity functions. Tariffs reduce international trade and increase regional trade—the spatial version of the standard effect of tariffs. Proofs of the next two propositions appear in the Appendix.

PROPOSITION 5: *Given a pair of productivity functions, trade frictions at the border that are small enough not to imply trade reversals weakly reduce trade between countries and weakly increase trade within countries.*

If productivity is allowed to adjust, this effect is amplified, creating a larger border effect. The standard implication in Proposition 5 is amplified in equilibrium, thereby increasing the elasticity of trade with respect to tariffs. We can formalize the result under some conditions. The first one is that production externalities decrease fast enough with distance. The restriction is necessary since we want the local increase in production of the protected good to influence local productivity more than the decrease in production in other countries. Given that most examples of regional externalities—like Silicon Valley or Route 128—involve relatively small regions, we do not believe that this is a very restrictive assumption.

We also need no trade reversals. The reason is that countries may start exporting a different good after imposing the tariff, and they potentially could export large amounts. This, however, does not imply that the elasticity of trade barriers is small, since with trade reversals the effective tariff, or friction, becomes zero. The last condition is necessary because of the potential multiplicity of equilibria in the model. Starting from an equilibrium without tariffs, we need to determine which of the potentially many equilibria we reach. Proposition 6 presents the result.

PROPOSITION 6 (Amplification effect): *In equilibrium, trade frictions at the border weakly reduce trade between countries and weakly increase trade within countries. The effects are larger than the effects given productivity functions if:*

- *Production externalities decrease fast enough with distance (high δ^F and δ^I);*
- *Trade frictions at the border are small enough not to imply trade reversals; and*
- *γ^F and γ^I are small enough so that, starting from an equilibrium with productivity functions (z^F, z^I), the sequence of functions $(T^F_\tau)^n(z^F, z^I)$ and $(T^I_\tau)^n(z^F, z^I)$, $n = 1, 2, \ldots$, converge. The operators T^F_τ and T^I_τ are defined for the economy with frictions.*

The last condition is a condition on γ^F and γ^I. If $\gamma^i = 0$, so the price function does not react at all to changes in (z^F, z^I), we are in the case of Proposition 1 and the operator converges in one step. If γ^i is very large, increases in z^i substantially increase productivity at different locations, which in turn implies large changes in land use patterns. Large changes in land use patterns may imply that the iterative procedure to find an equilibrium, which is the basis of the proof, may not converge. For small enough γ^i, the iterations always converge; these are the cases for which the proposition applies.

V. Restrictions on International Labor Mobility

Probably the specification of the model closer to reality is to allow for labor mobility inside a country but not across countries. Migration laws restrict mobility of workers in almost all nations in the world (Europe is an example for which the version presented so far is better suited). In this subsection, we modify the setup to allow workers to move freely inside a country, but not across countries. Free mobility of labor equalizes the utility of agents in a country. Hence, in this version of the model, utility levels vary between, but not within, countries. In order to incorporate the no-migration restriction, we can proceed in two ways. We can define the utility levels of agents in each country and let the population size be determined in equilibrium, or we can determine the population size in each country and let the utility levels be determined in equilibrium.

For the first case, we need to specify a utility level for each country. Let the number of countries be given by an integer NC and the two borders of each country be given by $\underline{B}(i)$ and $\bar{B}(i)$, for $i = 1, 2, \ldots, NC$, where $\underline{B}(i) = \bar{B}(i-1)$ by definition. Denote the utility level of agents in country i by $\bar{u}(i)$, $i = 1, 2, \ldots, NC$. Then, condition (i) in the definition of equilibrium becomes:

(i') *For all* $r \in [\underline{B}(i), \bar{B}(i))$, $i = 1, \ldots, NC$,

$$U(c^F(r)) = \bar{u}(i) \text{ and } U(c^F(S)) = \bar{u}(NC).$$

The rest of the analysis follows as in previous sections. Notice that the modified definition of equilibrium implies that, for U strictly increasing, $c^F(r)$ is a step function with constant value inside each country and different value between countries. That is, real wages vary between but not within countries.

For the second case, we need to determine the population of each country exogenously. Let $Pop(i)$ be the population size in country i. Then,

$$(15)\quad Pop(i) = \int_{\underline{B}(i)}^{\bar{B}(i)} (\theta(r)n^F(r) + (1-\theta(r))n^I(r))\,dr, \quad i = 1, \ldots, NC$$

is the equilibrium condition in country i's labor market. In this case the utility of agents in country i, $\bar{u}(i)$, is determined in equilibrium. Condition (i) in the definition of equilibrium then becomes:

(i'') *For all* $r \in [\underline{B}(i), \bar{B}(i))$, $i = 1, \ldots, NC$,

$$U(c^F(r)) = \bar{u}(i) \text{ and } U(c^F(S)) = \bar{u}(NC).$$

Population sizes in all countries are given by (15).

Again, all other features of the model presented in previous sections remain unchanged. The two cases presented above (exogenous utilities or population sizes) are equivalent. That is, there is a one-to-one mapping between countrys' population sizes and utility levels.[12] Since $c^F(\cdot)$ is not a continuous function, n^F, n^I, c^I, x^F, and x^I may not be continuous functions either. Hence, p_m has discontinuities at national borders. Nevertheless, the relative price function is still continuous in the absence of trade barriers.

VI. Numerical Examples

In this section, we illustrate the different equilibrium possibilities of the model with numerical examples. In all examples we use a Cobb-Douglas specification for the utility function and both production functions, so

$$x^F(r) = z^F(r)^{\gamma^F} n^F(r)^{\alpha^F} c^I(r)^{\beta^F},$$

$$x^I(r) = z^I(r)^{\gamma^I} n^I(r)^{\alpha^I}, \text{ and}$$

$$U(c^F(r)) = c^F(r)^{\beta}.$$

The basic parameterization used is given by $\gamma^F = \gamma^I = 0.09$, $\alpha^F = 0.8$, $\beta^F = 0.1$, $\alpha^I = 0.7$, $\beta = 0.8$, $\delta^F = \delta^I = 5$, and $\kappa^F = \kappa^I = 0.005$. These parameter values constitute the benchmark case from which we illustrate several possible equilibrium allocations.[13] All the results presented in the next subsection are for the case of perfect labor mobility using $\bar{u} = 1$. In order to construct an equilibrium, we also need to start the algorithm with an initial pair of productivity functions (z^F, z^I). This choice will select one of the potentially multiple equilibrium allocations of our model. To compute the benchmark case, we use a uniform distribution for both sectors. All other examples are computed using the pair of equilibrium distributions of the benchmark case as the initial productivity distributions. In all the computed examples, the equilibrium allocation has IG regions at the two boundaries. This characteristic of the examples presented is the result of our choice of initial distributions. Other initial distribution will lead to equilibria with FG regions at the edges.

Figure 2 presents the benchmark case. The top panel presents the price and mixed relative price functions, as well as land rents (divided by two for visibility). The bottom panel presents the excess supply functions in both sectors. As described above, there is a region at the center producing the FG, and the rest of the world produces the IG. The IG region on the left trades with the closest half of the FG region (the region to the left of the kink in the relative price curve). There is no trade between this IG region and the other half of the FG region; relative prices do not cover transport costs, so producers prefer to trade with regions that are closer. It is evident that regions trade with the closest region that produces the good they do not produce, and that relative prices of IGs are higher in FG-producing regions than in IG areas. Land rents decline as we approach the boundaries $-S$ and S or the boundaries between regions that produce different goods, given the lack of externalities from firms in the other sector or the absence of firms. Note that this decline is, however, modest at the boundaries $-S$ and S, which implies that the role played by the endpoints in the equilibrium allocation is relatively small. The concentration of economic activity in the FG region implies high productivity and, in most locations, higher land rents than in the IG sector. This is the result of the larger labor share in the FG production function and of spillovers that depend on the number of workers employed in the same sector in surrounding locations.[14]

A. *Transport Costs*

Transport cost parameters are of particular importance for the qualitative features of the equilibrium. If transport costs are very high, locations do not trade and the solution of the model is

[12] To see this, remember that the first-order conditions with respect to employment densities of the firms' problems are given by $g^F(z^F(r)) f_n^F(\bar{n}(r)\theta(r), c^I(r)) = U^{-1}(\bar{u}(i))$, and $p(r) g^I(z^I(r)) f_{n^I}^I(n^I(r)) = U^{-1}(\bar{u}(i))$, where $r \in [\underline{B}(i), \bar{B}(i))$. Hence, under Assumption A, a higher utility level in country i implies a lower employment density in both industries. Of course, changes in the utility function will change the productivity and prices at different locations and so the proof is more complex.

[13] Notice that in order for part (iv) of Assumption A to be satisfied, we need to use the following specification: $x^F(r) = \min[z^F(r)^{\gamma^F} + \underline{\varepsilon}, \bar{\varepsilon}] n^F(r)^{\alpha^F} c^I(r)^{\beta^F}$ and $x^I(r) = \min[z^F(r)^{\gamma^F} + \underline{\varepsilon}, \bar{\varepsilon}] n^I(r)^{\alpha^I}$. However, we can choose $\underline{\varepsilon}$ low enough and $\bar{\varepsilon}$ high enough so that the bounds do not play a role in the results. The parameter values chosen are such that all the other parts of Assumption A are satisfied.

[14] Since land rents always follow prices and productivity in the same way, we omit them in all other graphs.

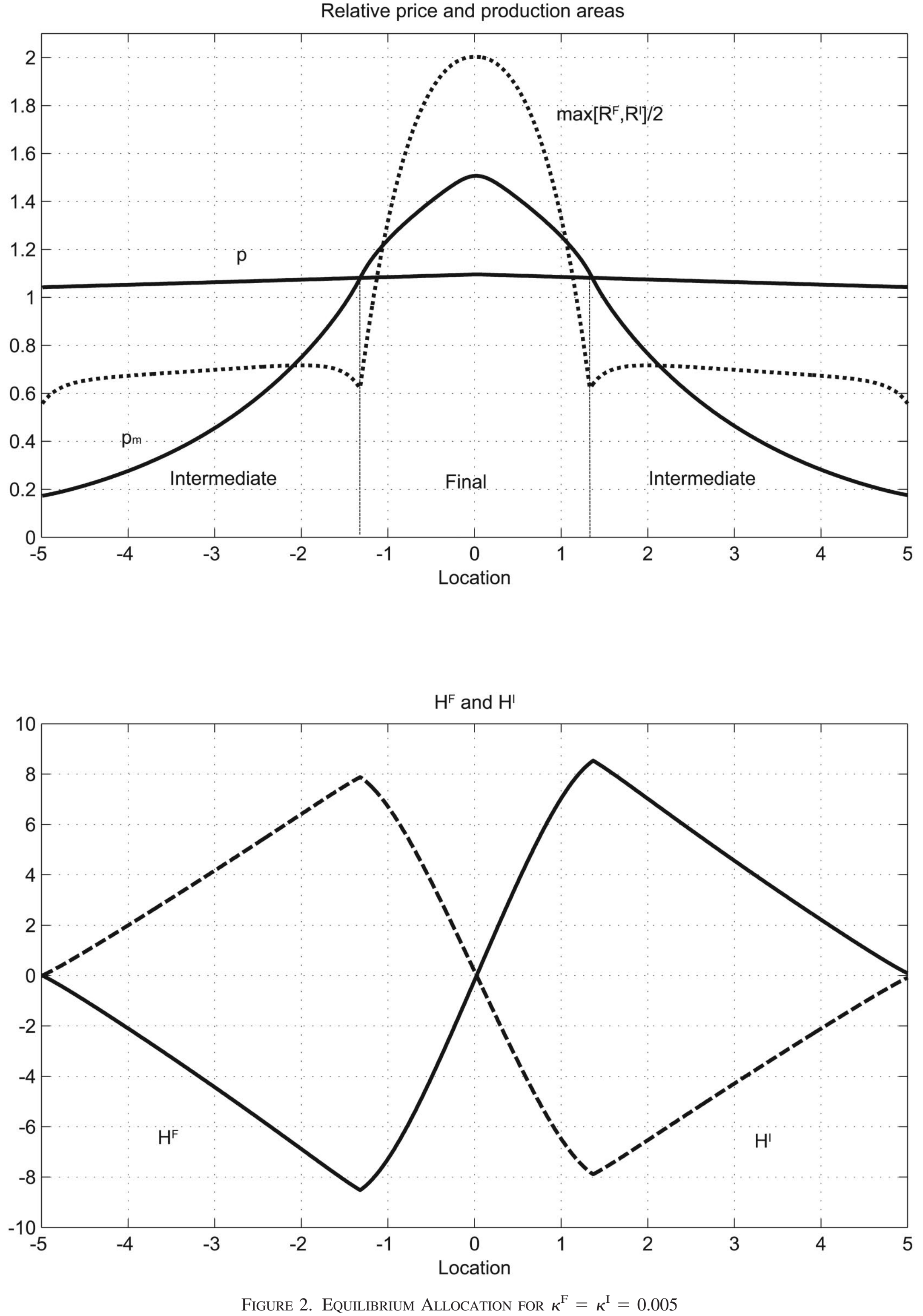

FIGURE 2. EQUILIBRIUM ALLOCATION FOR $\kappa^F = \kappa^I = 0.005$

autarchy at all locations. Since locations near the boundaries $-S$ and S are on average farther away from other locations, employment densities are lower near these boundaries.

If transport costs are low, regions specialize completely. This is the case for the FG sector in the example presented in Figure 2 for $\kappa^F = \kappa^I = 0.005$. Higher transport costs ($\kappa^F = \kappa^I = 0.1$) imply two distinct FG regions as shown in Figure 3. In this example, there are four regions in which there is trade within the region but no trade between regions. These areas can be identified as the areas between the kinks in the relative price curve. These kinks correspond to the locations at which both H^F and H^I are equal to zero. Trade flows are much lower than in the previous case, as is the level of economic activity and TFP, given the smaller production clusters. Population declines by 74 percent relative to the benchmark case. Hence, higher transport costs not only reduce trade, but also eliminate trade between certain regions completely. The intuition for these results is simple: as transport costs increase, the gains from concentrating production of the FG become smaller than the costs of shipping FGs and IGs long distances. This increases the bid rent of IG firms at the center of the FG cluster in Figure 2, which becomes higher than the bid rent of FG firms, and so a new IG region appears.

B. *Externality Parameters*

There are two parameters that govern the effect of production externalities on the distribution of economic activity and trade. The first parameter, γ^i, $i = F, I$, determines the extent to which spillovers affect output. In particular, it determines the elasticity of production with respect to z^i. A parameter γ^i close to one implies that productivity reacts almost one to one to changes in z^i. So, in this case, an increase in z^i affects productivity by the same amount no matter the level of z^i. For z^i close to zero, the effect of changes in z^i is much larger for firms that experience small spillover effects than for firms that experience large spillover effects. Figure 4 illustrates the effect of changes in γ^i on the excess supply functions, H^F and H^I. The solid line is the benchmark case with $\gamma^F = \gamma^I = 0.09$, and we let $\alpha^F = 0.75$. As we decrease γ^F to 0.08, the FG region expands and the IG regions at the boundary become smaller. A lower γ^F implies that there are fewer incentives to agglomerate economic activity in the FG sector, since the benefits of higher spillovers decrease, which expands the FG region. A decrease in γ^F also implies that the average spillover declines, and so there is a general level effect that decreases the level of economic activity in all FG areas. This decrease affects IG producers, since their good is used as an input only in the production of FGs. Total population decreases by 42.7 percent when $\gamma^F = 0.08$ and by 6.46 percent when $\gamma^I = 0.08$, relative to the benchmark case. A decrease in γ^I generates the opposite effect. IG areas expand and FG regions contract. As before, we obtain a general negative effect on the level of economic activity.

Hence, if an industry is in its first stages of innovation, where spillovers are likely to be large, the industry is geographically concentrated. As these spillovers become less important, we see more regions producing in that industry and lower productivity. This is reminiscent of what has happened in certain industries, for example, the computer industry. Firms started in very concentrated areas, and as their product became more standard, they moved to less expensive cities and regions.

The second parameter governing externalities is δ^i, $i = F, I$. A high δ^i implies that spillovers decline faster with distance, but the average level of spillovers remains constant. Numerical exercises for different values of δ^i are presented in the lower panel of Figure 4. As δ^i increases, economic activity concentrates in sector i. Output declines more sharply at the boundaries of the regions producing the good with higher δ^i. In contrast with the upper panel, in this case there is no level effect on output. Population declines only by 5.2 percent relative to the benchmark case when $\delta^F = 10$, and by 10.7 percent when $\gamma^F = 1$. The smaller is δ^F, the less dispersed is production within the FG region. For example, as communication technology becomes better, spillovers decline more slowly with distance. Some sectors, therefore, tend to expand and are less concentrated in a few clusters.

This seems consistent with the expansion of global manufacturing. In the twentieth century, manufacturing moved away from a couple of production centers in developed countries to many locations around the world.

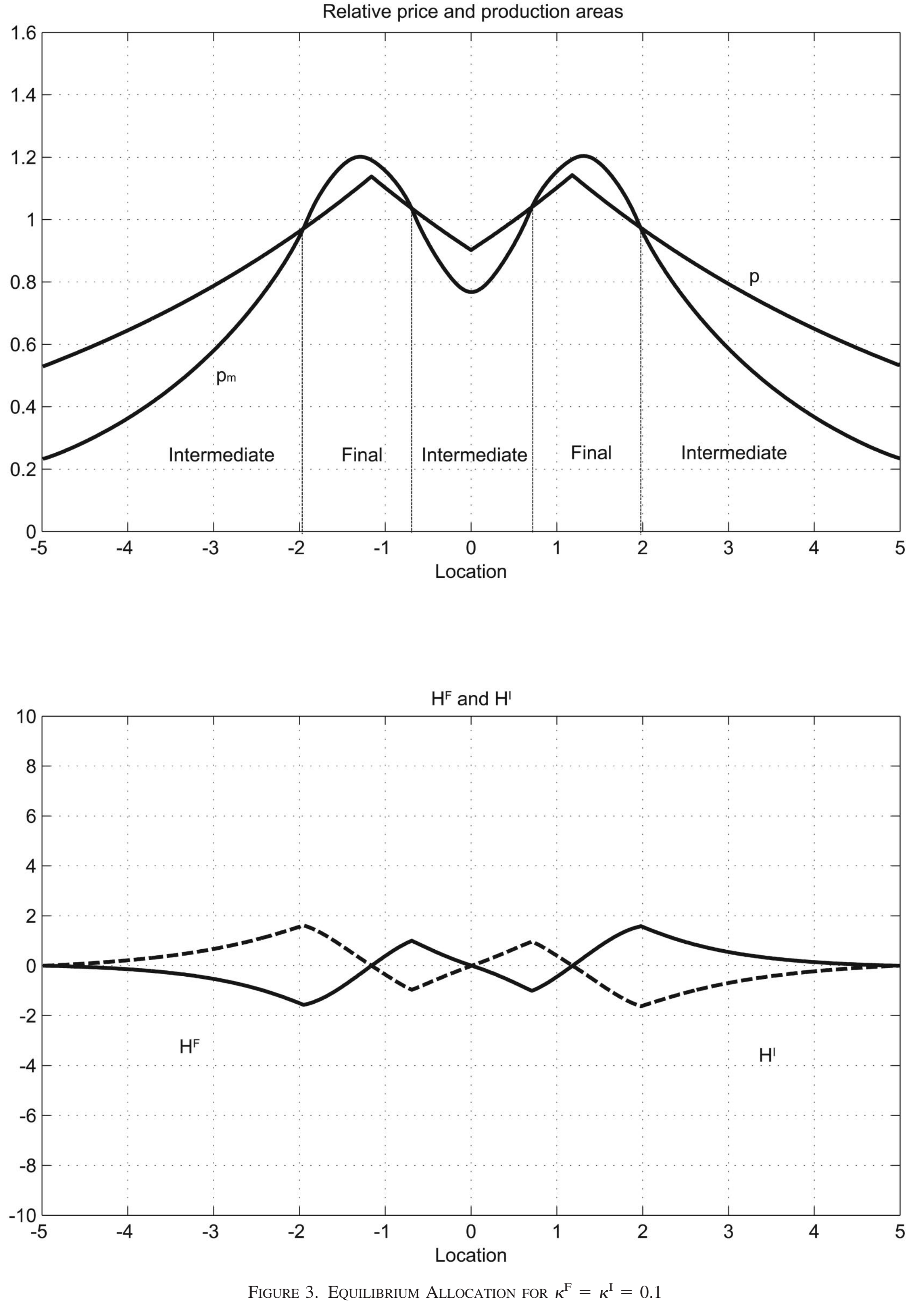

FIGURE 3. EQUILIBRIUM ALLOCATION FOR $\kappa^F = \kappa^I = 0.1$

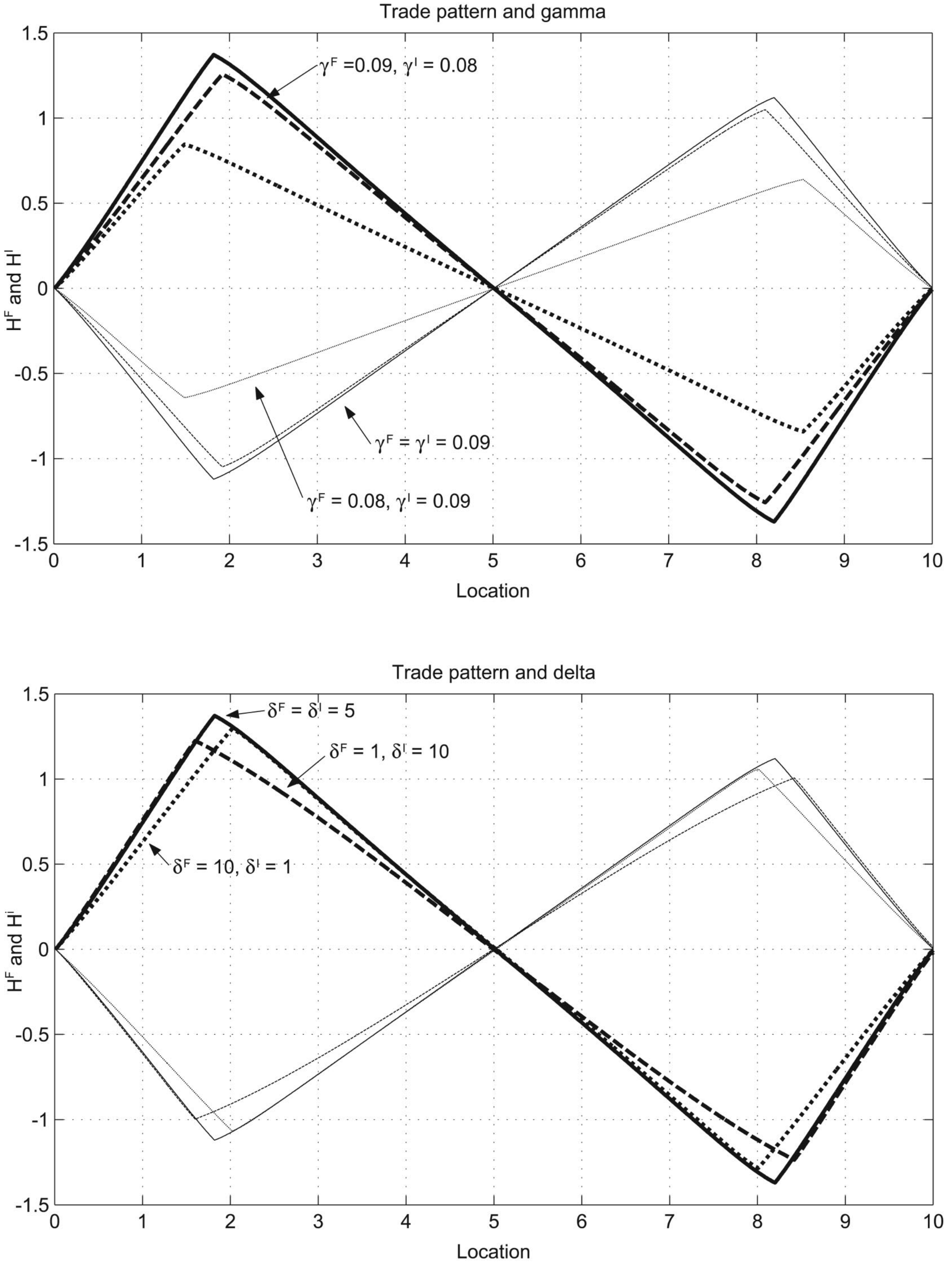

Figure 4. Equilibrium Trade Pattern for Different Externality Parameters ($\alpha^{F} = 0.75$)

C. *Labor Shares*

Labor shares, α^i, $i = F, I$, are also an important determinant of the distribution of economic activity. As the labor share of a particular industry increases, since the overall technology exhibits constant returns to scale, land shares decrease. Hence, increases in labor shares are always reductions in land shares. Figure 5 presents excess supply functions, H^F and H^I, for different labor shares in FG production. In all cases, labor shares in the IG sector are constant at 0.7. The solid line in the top panel represents the excess supply functions associated with the same exercise presented in Figure 2. FG production is very concentrated at the center. Labor shares are large and so production of FGs uses relatively small amounts of land. As we decrease the labor share, FG production becomes more land intensive and so FG areas expand. In the top panel we keep fixed the utility of agents, and therefore real wages, so employment in the economy can vary. As we decrease labor shares, employment decreases substantially, since labor is less important in production and real wages are fixed. These changes are larger, and in the same direction, as we lower the labor share further. However, the decrease in employment as we go from $\alpha^F = 0.8$ to 0.75 is much larger (89.6 percent) than the decline (34.6 percent) as we go from 0.75 to 0.70. The reason is that, in the first case, the FG sector becomes more intensive in land than in IGs. As a sector becomes more labor intensive, production concentrates in a few clusters. The large population decline implies a decline in the level of economic activity.

In order to control for the effect on population, we calculate another set of exercises where population sizes are fixed, and we vary utility levels. This eliminates the scale effect in the top panel and reverses the implication on concentration. As capital shares in the FG sector decrease, labor becomes relatively less expensive than land, and firms in the sector concentrate more. Real wages decrease as we make the FG technology less labor intensive ($\bar{u} = 1.05$, 1.00, and 0.89 for $\alpha^F = 0.8$, 0.75, and 0.7, respectively).

The exercise suggests that industries in which new workers can enter easily (e.g., low human capital) should be more concentrated the higher their labor shares. On the contrary, industries where entry of new workers is costly (e.g., high human capital requirements) should be less concentrated the larger their labor shares.

D. *Taxes and Border Effects*

In previous sections, we have argued that the theory generates amplified border effects. We illustrate this result using as a benchmark the equilibrium presented in Figure 2. Divide the world into three countries, where the first and third countries produce only the IG and the second only the FG. The equilibrium in Figure 2 then implies that the border between Countries 1 and 2 is at −1.32 and the border between Countries 2 and 3 is at 1.32. Let Country 2 impose a 40-percent tax on the imports of Country 1's IGs. The resulting allocation, given z^F and z^I, is presented in Figure 6. With import taxes, a new region in Country 1 produces FGs and a new region in Country 2 produces IGs. Nevertheless, Country 1 still exports IGs and imports FGs from Country 2.

The simulation presented in Figure 6 takes as given a pair of productivity functions. The functions are the equilibrium productivities for $\kappa^F = \kappa^I = 0.005$. Once we adjust the productivity functions, we obtain the equilibrium presented in Figure 7. Once agglomeration effects are taken into account, the tariff completely eliminates trade between Countries 1 and 2. Country 1 is in autarchy. The left side of the country produces the IG and the right side the FG. Because there is no trade between Country 1 and other countries, relative prices do not have to jump 40 percent at the border. The discontinuity is just large enough to guarantee that there is no excess supply of any of the goods in Countries 2 and 3. Country 2 produces both goods: the IG near its borders and the FG in the middle. Country 3 imports FGs from Country 2 and exports IGs. Trade flows between Countries 2 and 3 increase with respect to the original equilibrium with $\kappa^F = \kappa^I = 0.005$. This is why, as Anderson and Wincoop (2003) argue, it is important to control for average tariffs in estimations of the Gravity equation. The increase in the p_m function in Country 1 shows how firms operating near the border become more productive in the FG sector. The production externality, together with transport costs, amplifies the

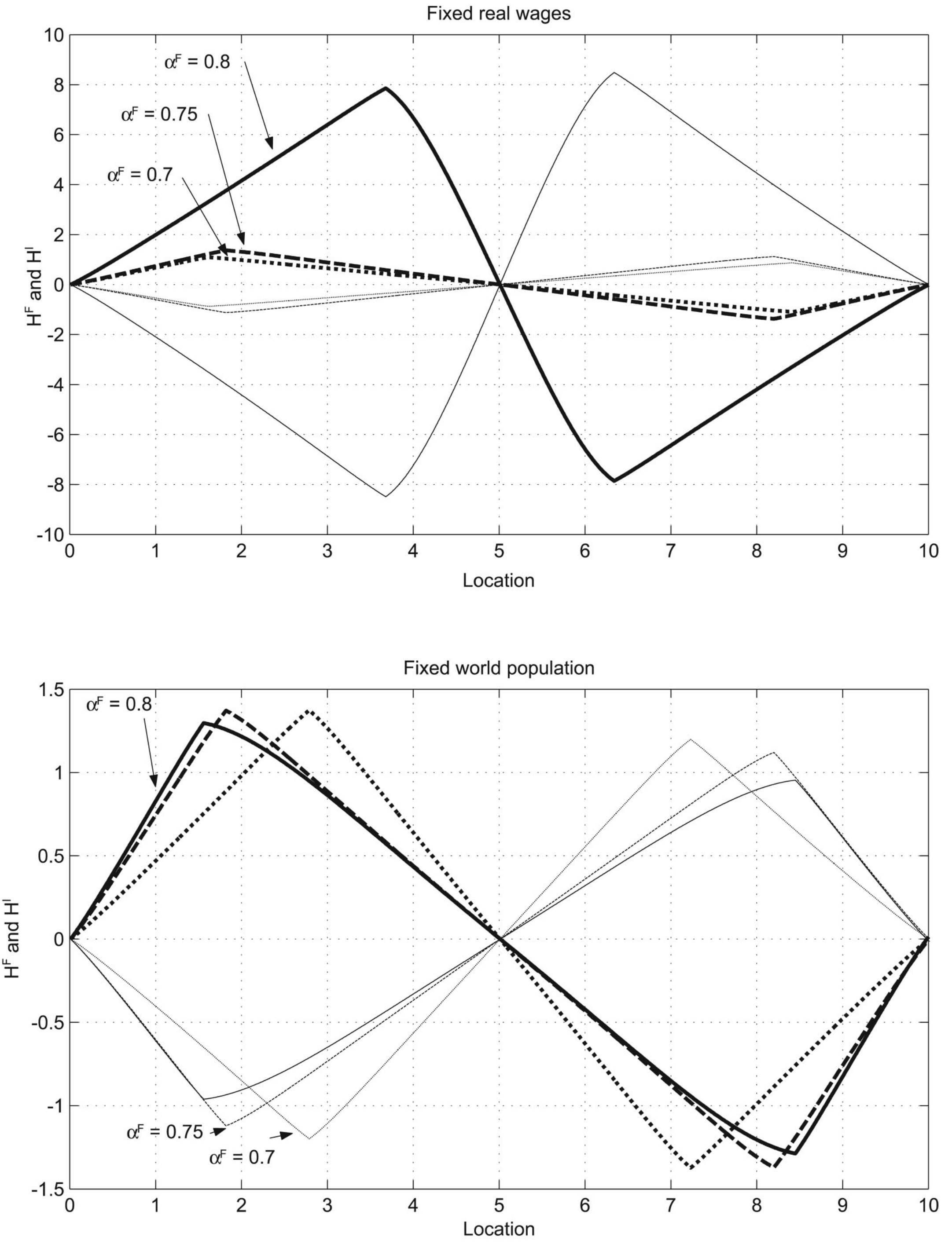

FIGURE 5. EQUILIBRIUM TRADE PATTERN FOR DIFFERENT LABOR SHARES

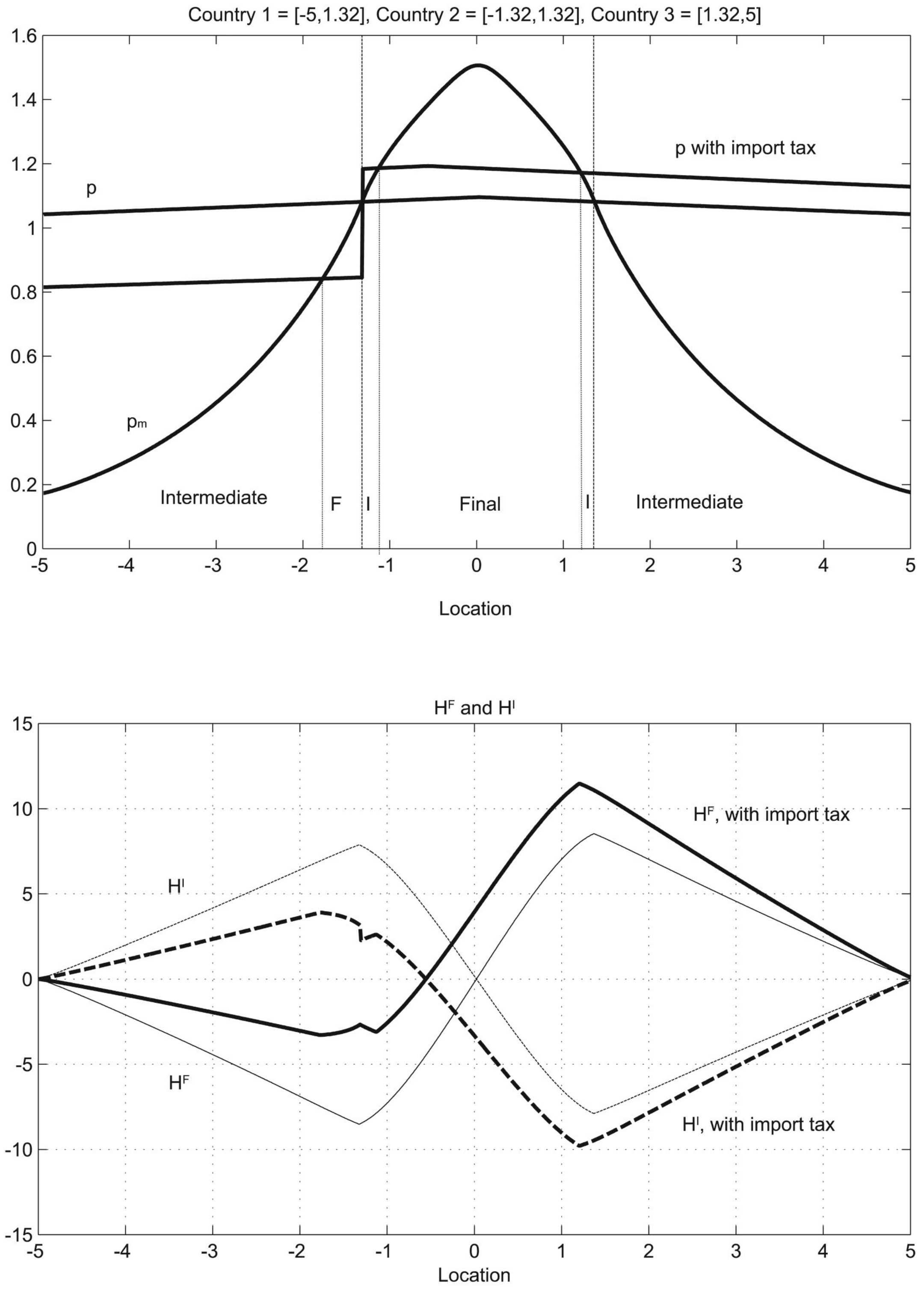

FIGURE 6. EQUILIBRIUM WITH IMPORT TAX AND FIXED PRODUCTIVITIES

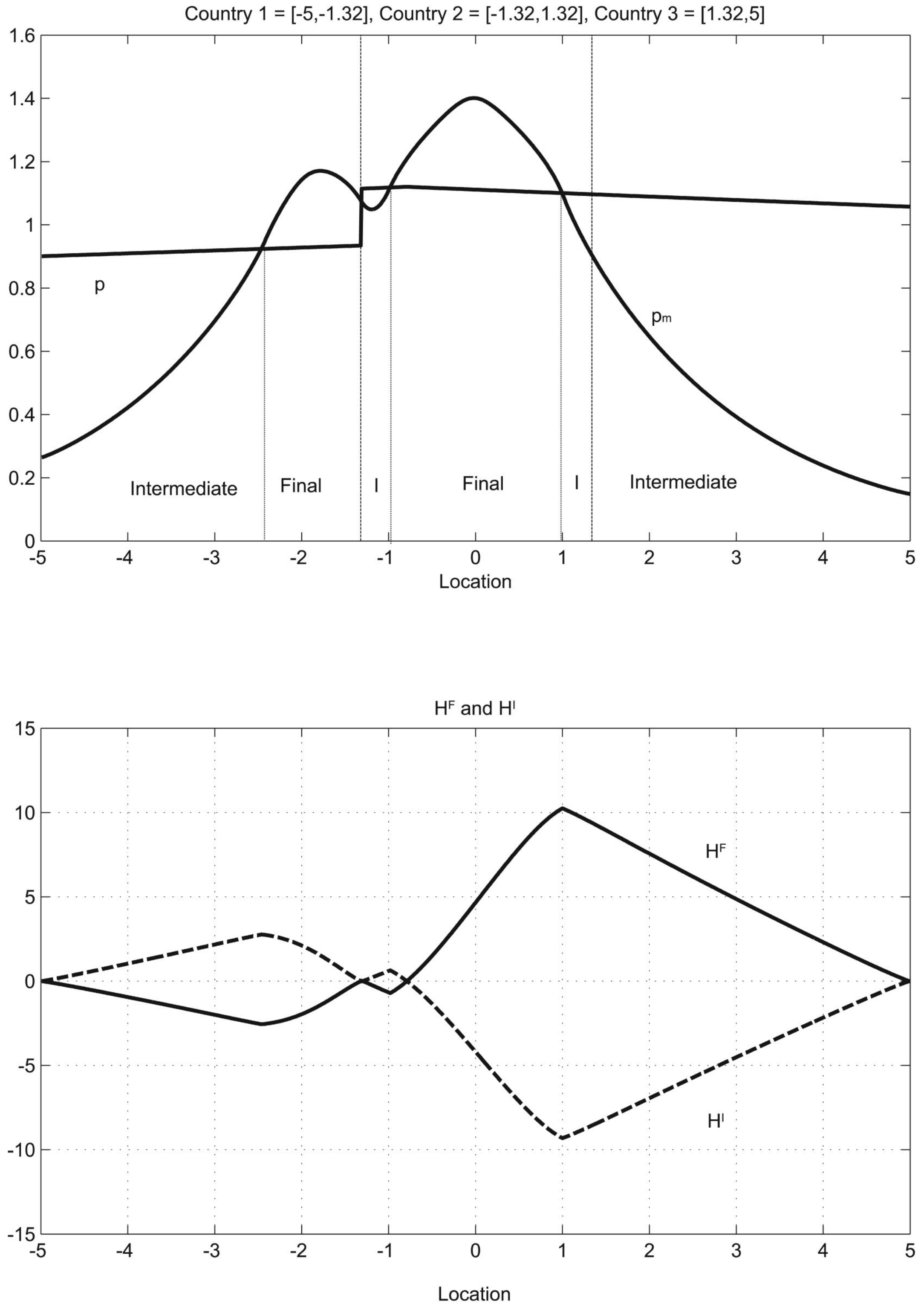

FIGURE 7. EQUILIBRIUM WITH IMPORT TAX

effect of the tariff to the extent that it completely eliminates trade between Countries 1 and 2. Regions in Country 1 trade more between themselves—because they are closer and there are transport costs—and Country 1 does not trade with the rest of the world. This is the mechanism that creates important border effects in the model. It implies a larger-than-standard elasticity of trade with respect to barriers.

E. *Taxes and Border Effects without International Labor Mobility*

As we described in Section V, we can set up the model restricting international labor mobility. The conclusions from the example shown in Figure 7 also hold in this case. Let the population sizes in each country be given by the exercise presented in Figure 2. Population in Countries 1 and 3 is small and equal, and population in Country 2 is substantially larger. We impose the tax and calculate the new equilibrium, holding population sizes in each country fixed. The results look very similar to the results in the case with international migration. Country 1 is in autarky. Again, we obtain a high elasticity of trade with respect to tariffs, higher than what standard models would predict.

An important difference between the example with international labor mobility and this one is that the current one gives us predictions on the utility levels of workers. Workers in Country 2—the one that imposes the tax—end up losing from the policy; the other two countries gain. Utility of workers in all previous examples is equal to 1. In this case, utility of workers is 1.035 in Country 1, 0.974 in Country 2, and 1.09 in Country 3. The average utility of workers in the world decreases to 0.99. Hence, the world as a whole is better off with free trade, but individual countries may gain from imposing tariffs; this can only be the case with migration restrictions. Note that the countries that gain do not have to be the countries that impose the tariffs. Since the FG is more intensive in labor than the IG (more intensive in land), as Country 2 substitutes production of FGs for IGs, it employs fewer people. Thus, wages have to decrease to eliminate the excess supply of labor. This is the main cause for the decline in utility. Conversely, the opposite effect is the main reason for the increase in worker utility in Country 1.

F. *Trade Policy and Multiple Equilibria*

In our theory, temporary trade policy can have permanent effects. Suppose Country 1 occupies the interval $[-5, -0.5]$ and Country 2 the interval $[-0.5, 5]$. Let $\kappa^F = \kappa^I = 0.02$. The equilibrium in this case implies that Country 1 exports IGs to Country 2. Suppose Country 2 imposes a tax of 20 percent on the imports of IGs from Country 1. In the new equilibrium, with perfect labor mobility and tariffs, both countries are in autarky. What happens if we now remove the tariff? Nothing! The new equilibrium without tariffs is identical to the equilibrium with barriers. The reason is that productivities change in such a way that countries would not trade even if it were costless. Figure 8 presents the original equilibrium, the equilibrium given productivities, and the new equilibrium with and without taxes. Autarky is not the only way this can happen; trade reversals are another possibility. Country 1 may become so productive at producing FGs that it may start exporting them. In this case, the tariff on IGs is not effective and so reducing or removing it has no effect. Permanent effects of trade policy, as the one illustrated above, suggest a potential explanation for why, in some cases, trade liberalization has not led to large increases in trade flows. There are, however, examples in which removing or reducing the tariff *does* change the equilibrium allocation. In fact, this is the case in the equilibrium presented in Figure 7.

VII. Conclusion

We have presented a theory of the spatial distribution of economic activity and the associated trade patterns. On the methodology side, the model presented uses a constant returns-to-scale technology with production externalities. This helps us model firms' location and land use decisions with a continuum of regions, which has the advantage of allowing for a very rich variety of concentration and specialization patterns in a model that is suitable for both analytical and computational study. This setup has allowed us to talk about changes in fundamentals, as well as trade policy, without loosing the ability to derive conclusions for *both* within- and between-country trade. This flexibility comes at a cost, namely, that the production externality is a black box—a reduced form representation of the interactions between firms.

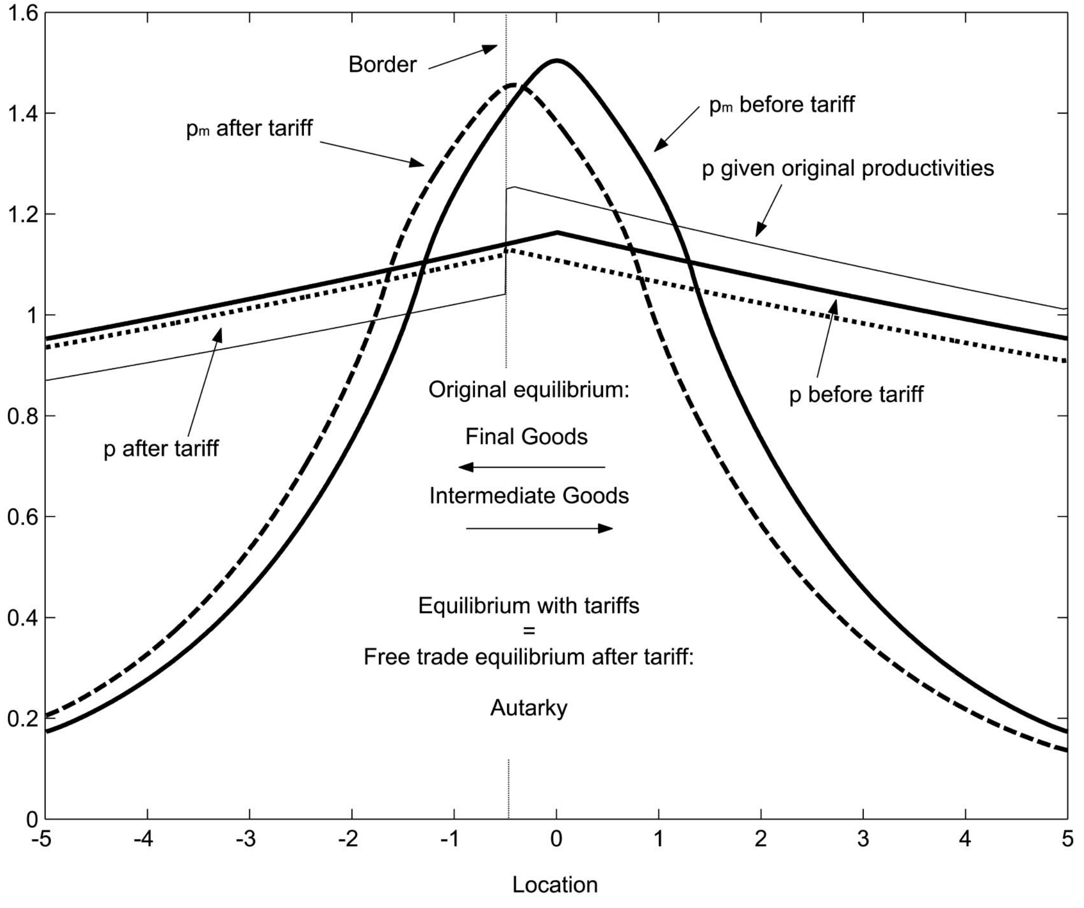

FIGURE 8. TRADE POLICY AND MULTIPLE EQUILIBRIA

Understanding trade through the concentration and specialization patterns in space provides a novel rationalization of several trade facts. In our framework the distribution of economic activity depends on the size of transport costs and externality parameters, and these fundamentals determine intra-national and international flows of goods. Our analysis emphasizes that including space, as we have done, differentiates clearly the role of transport costs and tariffs. The change in specialization created by border frictions is amplified by the agglomeration effects, transport costs, and the spatial structure, resulting in an amplification of frictions at national borders—a higher than standard elasticity of trade with respect to barriers. This conclusion is not affected by assumptions on international labor mobility. The magnitude of the amplification is directly related to the magnitude of agglomeration forces. We hope this paper stimulates empirical studies of the link between border and agglomeration effects.

The model is consistent with estimations of the gravity equation both within and across countries. Results on the gravity equation for regions inside the European Union and for states in the United States may corroborate this conclusion. The implication that equipment prices are higher in developing countries than in developed economies is a natural outcome of having a continuum of regions and transport costs. Hence, although the model does deliver the result, it would be interesting to see if the differences in relative prices are of a magnitude consistent with transport costs.

Our setup can be used to understand a wide range of regions and policies. In particular, one could start with other initial productivity functions that yield different spatial configurations. As pointed out in Section II, since the equilibrium of the model may not be unique, the initial production structure in a region, or group of countries, may determine the equilibrium, and so history matters. Furthermore, the paper highlights how temporary trade policy can select a particular equilibrium allocation. In this sense, the history of trade policy matters for the current allocation. This may rationalize cases in which trade liberalization has had disappointing effects.

A possible extension of the theory is to study the evolution of concentration and specialization patterns as economies develop.[15] The model has predictions on the link between these measures, transport costs, and productivity growth; but, as it stands, it is static. Another extension is to add several consumption goods. This may help explain clusters in a variety of industries and the associated patterns of consumption, with the potential to understand the "home-bias in consumption puzzle." These extensions are left for future research.

[15] See Sukkoo Kim (1995), Jean M. Imbs and Romain Wacziarg (2003), and Karl Aiginger and Stephen W. Davies (2004) for empirical evidence.

Appendix: Proofs of Propositions 3, 4, 5, and 6

PROOF OF PROPOSITION 3:

The proposition can be restated as: If $H^F(s) < 0$ for all $s \in [r, r']$, $r \neq r'$, $\theta(r) = 0$ and $\theta(r') = 1$, then $p(r') > p(r)$. If $H^F(s) > 0$ for all $s \in [r, r']$, $r \neq r'$, $\theta(r) = 1$ and $\theta(r') = 0$, then $p(r') < p(r)$. The proof is an immediate consequence of the no-arbitrage conditions (12) and (13). Take the case where $H^F(s) < 0$ for all $s \in [r, r']$, $r \neq r'$, $\theta(r) = 0$, and $\theta(r') = 1$; then condition (12) implies that $p(r) = e^{-(\kappa^F + \kappa^I)|r - r'|}p(r')$, which yields the result for $\kappa^F + \kappa^I > 0$.

If $H^F(s) > 0$ for all $s \in [r, r']$, $r \neq r'$, $\theta(r) = 1$, and $\theta(r') = 0$, then condition (13) implies that $p(r) = e^{(\kappa^F + \kappa^I)|r - r'|}p(r')$ and so $p(r') < p(r)$.

PROOF OF PROPOSITION 4:

The proposition can be restated as: If $|r - s| > |r - s'|$ and $\theta(r) + \theta(s) = \theta(r) + \theta(s') = 1$, then $Tr(r, s) \leq Tr(r, s')$.

If $|r - s| > |r' - s|$ and $\theta(r) + \theta(s) = \theta(r') + \theta(s) = 1$, then $Tr(r, s) \leq Tr(r', s)$. Let s be such that for all $r' \in (r, s)$, $|H^F(r')| > 0$. Then, if $H^F(s) > 0$, $\partial H^F(s)/\partial r < 0$, and if $H^F(s) < 0$, $\partial H^F(s)/\partial r > 0$. Hence $Tr(r, s) \leq Tr(r, s')$.

Let s be such that there exists an $r' \in (r, s)$ such that $H^F(r') = 0$. Then, $Tr(r, s) = 0$ and $Tr(r, s') \geq 0$. The second part of the proof for r and r' is analogous.

PROOF OF PROPOSITION 5:

Let the intervals $[B_1, B_2]$ and $[B_3, B_4]$ represent Country 1 and 2, respectively, where $B_2 \leq B_3$. Without loss of generality, assume that Country 1 is exporting the IG to Country 2 (so by current account balance Country 2 exports the FG to Country 1). Define trade between Country 1 and 2 by

$$Tr_s^B \equiv Tr(B_2, B_3) = \begin{cases} \min\{|H^F(B_2)|, |H^F(B_3)|\} & \text{if } |H^F(r')| > 0 \ \forall r' \in (B_2, B_3) \\ 0 \text{ otherwise.} \end{cases}$$

Let $(S_1^1, S_2^1, ...)$ be a sequence of numbers such that

$$S_1^1 = B_1,$$

$$S_2^1 = \min[\arg\max_{s > B_1} H(s),\, B_2],$$
$$S_i^1 = \min[\arg\max_{s > S_{i-1}^1} H(s),\, B_2],$$

and define n^1 by $n^1 \equiv \min\{n : S_n^1 = B_2\}$. We can build a sequence of numbers $(S_1^2, S_2^2, \ldots, S_{n^2}^2)$ in a parallel way, where $S_1^2 = B_3$. Then, trade within Country $j = 1, 2$ can be defined by

$$Tr_s^W(j) \equiv \sum_{i=1}^{n^j-1} [\max_{r \in [S_i^j, S_{i+1}^j]} |H^F(r)e^{-\kappa^F|B_{j+1}-r|}|] - \max[|H^F(S_1^j)e^{-\kappa^F|B_{j+1}-S_1^j|}|, |H^F(S_{n^j}^j)e^{-\kappa^F|B_{j+1}-S_{n^j}^j|}|].$$

We need to show that the presence of a trade friction, τ, reduces Tr_s^B and increases $Tr_s^W(j)$, $j = 1, 2$.

Given the assumed flow of trade, again without loss of generality, assume that Country 2 imposes a trade tariff on the imports of IGs from Country 1 (any effective friction at the border may be reduced to this example). Then $p(r)$ decreases for $r \in [B_1, B_2]$ and $p(r)$ increases for $r \in [B_3, B_4]$, as illustrated in Figure 1. This implies, under Assumption A, that $x^F(r)$ decreases weakly for $r \in [B_3, B_4]$ and so, since transport costs have not changed, that $|H^F(B_2)|$ decreases weakly (see Lemma 1 in Rossi-Hansberg, 2003). Country 1 is exporting IGs so $H^F(B_2) < 0$. A decrease in $p(r)$ for $r \in [B_1, B_2]$ implies that $x^F(r)$ increases weakly for $r \in [B_1, B_2]$ and so $H^F(B_2) < 0$ increases weakly or $|H^F(B_2)|$ weakly decreases. Hence the trade friction implies a reduction in Tr_s^B.

To show that $Tr_s^W(1)$ increases, first notice that the expression

$$\max[|H^F(S_1^j)e^{-\kappa^F|B_{j+1}-S_1^j|}|, |H^F(S_{n^j}^j)e^{-\kappa^F|B_{j+1}-S_{n^j}^j|}|]$$

takes the values $|H^F(B_1)e^{-\kappa^F|B_2-B_1|}|$ and $|H^F(B_2)|$ for $j = 1$. Notice also that

$$\max_{r \in [B_1, S_2^j]} |H^F(r)e^{-\kappa^F|B_2-r|}| \geq |H^F(B_1)e^{-\kappa^F|B_2-B_1|}| \geq 0$$

and

$$\max_{r \in [S_{n^1}^j, B_2]} |H^F(r)e^{-\kappa^F|B_2-r|}| \geq |H^F(B_2)| > 0.$$

We have proven above that $|H^F(B_2)|$ weakly decreases. Since $p(r)$ decreases for $r \in [B_1, B_2]$ and this implies that $x^I(r)$ decreases weakly and $x^F(r)$ increases weakly for $r \in [B_1, B_2]$,

$$\sum_{i=2}^{n^1-2} \max_{r \in [S_i^1, S_{i+1}^1]} |H^F(r)e^{-\kappa^F|B_2-r|}|$$

increases weakly. Locations with $r < B_1$, also experiences a decrease in the price of IGs. As a result, $H^F(B_1)$ increases weakly. However, by definition, the increase in

$$\max_{r \in [B_1, S_2^j]} |H^F(r)e^{-\kappa^F|B_2-r|}|$$

has to be equal or larger. Hence, $Tr_s^W(1)$ increases weakly. Exactly the same logic applies for Country 2. Hence, $Tr_s^W(1)$ and $Tr_s^W(2)$ increase weakly.

PROOF OF PROPOSITION 6:

First note that the tax creates the same effects described in Proposition 5, plus it changes productivities. Let $p(r)$ be the relative price of an equilibrium without trade frictions and let $p^{\tau}(r)$ be the relative price of the short-term equilibrium (given productivity functions) with trade frictions τ. Without loss of generality, assume that Country 1, $[B_1, B_2]$, exports the IG to Country 2, $[B_3, B_4]$, where $B_2 \geq B_3$. As discussed above, the frictions create a discontinuity in p^{τ} so that $p^{\tau}(r) < p(r)$ for $r \in [B_1, B_2]$ and $p^{\tau}(r) > p(r)$ for $r \in [B_3, B_4]$. This implies that

$$\int_{B_1}^{B_2} [1 - \theta_{\tau}(r)]\, dr \leq \int_{B_1}^{B_2} [1 - \theta(r)]\, dr$$

and

$$\int_{B_3}^{B_4} \theta_{\tau}(r)\, dr \leq \int_{B_3}^{B_4} \theta(r)\, dr$$

where $\theta_{\tau}(r)$ is the fraction of land use to produce FGs at location r in the "short-term" equilibrium with frictions (given productivity function). That is, a smaller or equal amount of land is specialized in the production of the IG in Country 1 and a smaller or equal amount of land is specialized in the production of the FG in Country 2. This implies that a larger or equal proportion of land is used for the production of the FG in Country 1 and a larger or equal proportion of land is used for the production of the IG in Country 2. By Assumption A (see Lemma 1 in Rossi-Hansberg, 2003) $p^{\tau}(r) < p(r)$ implies that $x_{\tau}^{I}(r) < x^{I}(r)$ and $x_{\tau}^{F}(r) > x^{F}(r)$ for $r \in [B_1, B_2]$, and so Assumption A (ii) and (iii) imply that $n_{\tau}^{I}(r) < n^{I}(r)$ and $n_{\tau}^{F}(r) > n^{F}(r)$ for $r \in [B_1, B_2]$. Similarly for Country 2, $p^{\tau}(r) > p(r)$ implies that $x_{\tau}^{I}(r) > x^{I}(r)$ and $x_{\tau}^{F}(r) < x^{F}(r)$ for $r \in [B_3, B_4]$, and so Assumption A (ii) and (iii) imply that $n_{\tau}^{I}(r) > n^{I}(r)$ and $n_{\tau}^{F}(r) < n^{F}(r)$ for $r \in [B_1, B_2]$. Hence, there exists a δ^F and a δ^I such that

$$T_{\tau}^{F}(z^F, z^I)(r) > z^F(r)\ \forall r \in [B_1, B_2],$$
$$T_{\tau}^{I}(z^F, z^I)(r) < z^I(r)\ \forall r \in [B_1, B_2],$$

and

$$T_{\tau}^{F}(z^F, z^I)(r) < z^F(r)\ \forall r \in [B_3, B_4],$$
$$T_{\tau}^{I}(z^F, z^I)(r) > z^I(r)\ \forall r \in [B_3, B_4].$$

The high pair of (δ^F, δ^I) is needed so that the lower spillover coming from the reduction of employment in the FG industry in Country 2, for example, does not dominate the higher spillover coming from the increase in production of FGs in Country 2. The level of spillovers is not important; the rate of decline with distance is.

We need to show that the change in productivities described above holds for further iterations; that is, if we keep applying the operators T_{τ}^{F} and T_{τ}^{I}, we get monotone effects on productivity of final and IG production. We also need to show that these changes in productivity lead to less international trade and more regional trade. To show that the effects on productivity of further iterations are monotone for some δ^F and a δ^I, notice that higher $z^F(r)$ in Country 1, for example, weakly increases $\theta(r)$ and $n^F(r)$ for $r \in [B_1, B_2]$. This, by Lemma 1 in Rossi-Hansberg (2003), increases the relative price of IGs, in Countries 1 and 2, which in turn increases the production of IGs in both countries. Hence, the effect in productivity has to weakly dominate the effect in relative prices in Country 1. So Country 1 employs a larger or equal number of workers in the FG sector, which implies that for δ^F high enough (i.e., this effect dominates the effect of fewer FG workers in Country 2),

$$(T_{\tau}^{F})^2(z^F, z^I)(r) > T_{\tau}^{F}(z^F, z^I)(r) > z^F(r)\ \forall r \in [B_1, B_2].$$

The same argument applies for all other changes in productivity in both countries. Hence, there exist a δ^F and a δ^I such that changes in productivity are monotone in each iteration.

We now turn to show that this increase in productivity implies a further reduction in trade flows between countries and a further increase in trade within nations. Clearly, the first iteration implies the effects in Tr_s^B and $Tr_s^W(i)$, $i = 1, 2$ that we analyzed in Proposition 5. If we can show that the increases in productivity described above also imply a reduction in Tr_n^B and an increase in $Tr_n^W(i)$, $i = 1, 2$ (where the subscript n denotes that this is the nth iteration of the operators), then we have proved the existence of the amplification effect, if the successive application of the operators T_τ^F and T_τ^I converges. For this, notice that a lower productivity of Country 2 in the production of FGs implies that Country 2 produces fewer FGs; this implies, by Lemma 1, a lower relative price of IG but, as discussed above, the effect in productivity dominates, so the final result is fewer exports of FGs from Country 2. Hence $|H^F(B_3)|$ and $|H^F(B_2)|$ fall, since we are assuming no trade reversals. Therefore

$$Tr_e^B = Tr(B_2, B_3)$$

decreases. Since the change in the productivities is monotone, if the sequence of iterations converges, the reduction in Tr_e^B is larger than the reduction in Tr_s^B because of the adjustment in productivities.

To show that regional trade increases, notice that the change in productivities implies that, for example, Country 1 is producing more FGs and fewer IGs (the effect in productivities weakly dominates the effect in price). Since the country is still exporting the IG (no trade reversals), this implies that regional trade has to increase. This implies that, as in the proof for Proposition 5,

$$\sum_{i=2}^{n^1-2} \max_{r \in [S_i^1, S_{i+1}^1]} \left| H^F(r) e^{-\kappa^F |B_2 - r|} \right|$$

increases and the other terms weakly increase by construction. Therefore, the increase in productivities increases $Tr_e^W(i)$, $i = 1, 2$. Hence, if the sequence of iterations converges, the equilibrium effect on regional trade is larger than the "short-term" effect.

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