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Trade, spatial separation, and the environment

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Abstract

We develop a simple two-sector dynamic model to show how pollution can provide a motive for trade by spatially separating incompatible industries. We assume that the production of ‘‘Smokestack’’ manufactures generates pollution, which lowers the productivity of an environmentally sensitive sector (‘‘Farming’’). Two identical, unregulated countries will gain from trade if the share of world income spent on Smokestack goods is *high*. In contrast, when the share of world income spent on the dirty good is *low*, trade can usher in a negatively reinforcing process of environmental degradation and real income loss for the exporter of Smokestack goods.

Keywords: Two-sector dynamic model; Pollution; Production externality

JEL classification: F10; Q20

1. Introduction

In the last few years economists and environmentalists have engaged in a lively debate over the possible effects of international trade on the environment.[1] Perhaps one of the most serious limitations of much of the recent theoretical work by

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[1] See Grossman and Krueger (1993) and Selden and Song (1994) for empirical work. For theory, see Baumol and Oates (1971); Markusen (1975), (1976); Copeland and Taylor (1994), (1995), and Rauscher (1991). Dean (1992) and Beghin et al. (1994) are useful surveys of the trade and environment literature. Lopez (1994) and Smulders (1994) examine growth and environment issues.

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economists is that it ignores the long run effects of industrial pollution on productivity in environmentally sensitive sectors. Most of the existing work assumes that pollution is harmful only because consumers suffer a disutility cost from pollution. But if pollution also affects productivity, then it can jeopardize long run sustainability and lower the competitiveness of environmentally sensitive industries. And hence if trade affects pollution, then it may also affect long run income as well as amenity values. For many environmentalists, the neglect of these feedback effects is a key weakness of the standard economic approach to trade and the environment.

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. Current estimates of environmental damage suggest that such external effects are not negligible. Pearce and Warford (1993), (p. 28) report damage estimates from a low of 0.5–0.8% of GNP for the Netherlands, to 4.6–4.9% of GNP for Germany, to a high of 10% of GNP for Poland. Specific industry studies are also available.[2]

Despite the apparent link between the output of heavy industry and damage to environmentally sensitive sectors, economists are often sceptical of the potential for international trade to play a significant role in reinforcing or reversing current trends. In this paper we show that when production externalities are important, trade may in fact play a key role in determining environmental outcomes by spatially separating incompatible industries.

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 pollution from other sectors of the economy. Trade can play a useful role in allowing incompatible industries to move away from each other. By separating incompatible industries, trade can reduce the damage from cross-sectoral production externalities and can generate productivity gains for the world as a whole. 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. We show that in some cases, the country that ends up with the polluting industry may suffer not only from reduced productivity in environmentally sensitive sectors, but also from a terms of trade deterioration that is brought on by its own environmental degradation.

We construct a very simple dynamic model to make transparent the role trade can play in separating incompatible industries. There are only two industries: a smokestack manufacturing industry which we denote by M, and an environmental-

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[2] A recent comprehensive study of European Forests by the International Institute for Applied Systems concludes that sulphur emissions alone cost Europe $30 billion per year in forest losses (for a review of this research see Carrier and Krippi (1990)). Other supporting evidence can be found in the U.N. Environmental Data Report (1993) and FAO (1977).

ly sensitive industry such as agriculture, fishing or forestry denoted by A. For simplicity we refer to A as Farming output, but it should be thought of as a generic output from any environmentally sensitive sector.

We define a stock variable, ‘‘environmental capital’’, which is meant to capture the productivity-relevant aspects of environmental quality. The Smokestack industry emits pollution, and over time the flow of these pollutants degrades the nation’s environmental capital. Since we assume that the free flow of services from the environment are inputs into farming, a lower stock of environmental capital necessarily lowers the productivity of other primary inputs in the farming sector. Throughout we assume that pollution stays within the country of origin, that there is no regulation of emissions from Smokestack, and that emissions do not create a direct utility cost to consumers. This simple framework isolates the impact of free trade when industrial pollution creates a negative cross-industry externality.

Within this framework we derive several surprising results. First, we show that opening a country to trade at world prices that are arbitrarily close to autarky prices can lead to a very large discrete change in environmental quality. As Baumol and Bradford (1972) showed, a country’s long run production possibility set may be nonconvex when there are cross-sectoral production externalities. With nonconvexities in the production set, an open economy has a tendency to specialize in production, and there is the potential for a small price change to result in a large expansion of the pollution-intensive sector.

Second, we find that two identical countries can gain from trade. The standard explanation for trade between similar countries rests on the benefits of concentrating industries with increasing returns to scale. Here we find that the benefits of separating incompatible industries provides an alternative mechanism through which identical countries can gain from trade. As the environmental literature has pointed out (e.g., Helfand and Rubin, 1994) the presence of nonconvexities suggests that policy in many cases should encourage environmental damage to be spatially concentrated: if one industry harms another, then one solution is to separate them. We find that such spatial separation must occur as a result of trade: Endogenously evolving productivity differences will provide market incentives for the two countries to specialize in production. Thus, in some cases, an efficient allocation of production across countries can occur without the need for any environmental policy.

Third, the welfare implications of trade are quite surprising. We find that if the share of world income spent on the dirty product is large, then free trade must be welfare-enhancing for two identical countries. Conversely, if the share of world income spent on clean products is large, then one of the two countries must lose from trade. Moreover, losses are more likely the faster is the environment’s regeneration rate and the smaller is the negative externality!

Lastly, once we introduce nonidentical countries we show that free trade can lock in the wrong (inefficient) pattern of specialization across countries. Trade can leave the country with the most resilient environment specialized in the clean good, while its trading partner produces all of the dirty good. Similarly, trade can leave the most populous country diversified in production, when production efficiency requires just the opposite.

This paper integrates two strands of the literature, one from environmental economics, and the other from international trade. Our model can be interpreted as an open economy and dynamic extension of the Baumol and Bradford (1972) model of pollution. It also bears a strong family resemblance to the open economy models that Melvin (1969), Panagariya (1981), and Ethier (1982) developed to analyze external economies of scale.

In the environment literature, it is well known that pollution externalities can lead to nonconvexities 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 part, this seemingly benign neglect has arisen because much of the relevant policy analysis has been carried out in a partial equilibrium framework; and in part, because some authors, such as Burrows (1986) have argued that the theoretical difficulties that nonconvexities create are of little practical significance for pollution policy. In contrast, we show that nonconvexities generated by pollution externalities can play a critical role in determining the pattern of trade, the gains from trade, and the environmental consequences of free trade.

In the international trade literature, nonconvexities play a central role. During the past twenty years, much of the new trade theory has examined increasing returns to scale as a determinant of trade. Many authors have modelled increasing returns as a positive externality external to firms, but internal to an industry (see Helpman, 1984, for a review). This generates potential gains from trade from concentrating industries with external economies in one location. In this paper, we consider the implications of a negative cross-industry externality.[3] Here the motive for trade is to spatially separate industries. In what follows we uncover a number of interesting parallels and contrasts between the implications of these two different, but similar, motives for trade.

In many ways our analysis continues a line of research originating with Frank Graham in the 1920's. Graham's argument was simply that free trade can create losses if trade changes the composition of national output in such a way as to reduce overall productivity. These trade-induced productivity losses then need to be weighed against terms of trade gains to determine the overall welfare consequence of international trade. As Ethier (1982) so clearly showed, Graham was right—free trade can create losses if there are external economies in one sector—although the conditions under which his hypothesis held were quite surprising and at odds with conventional wisdom. Here we identify another

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[3] Panagariya considered negative externalities that were internal to an industry, and Ethier also briefly considered this case. This type of externality, however, tends to make the production frontier concave, and hence has much different effects.

channel through which overall productivity can fall (or rise!) when a country enters into international trade. And, like Ethier (1982), we provide results that were initially at odds with our own intuition regarding the welfare (and environmental) consequences of free trade.

The structure of the paper is as follows. We set up a simple dynamic model in Section 2 and study autarky in Section 3. In Sections 4–6, we consider the effects of trade. In Section 7, we briefly discuss possible extensions. Section 8 concludes.

2. The model

There are two primary factors: Labor (L) and the stock of environmental capital (K). The level of K is given at any moment in time, but may be degraded or enhanced over time, depending on the flow of pollution and nature's regenerative capacity. We assume that K evolves according to:[4]

$$\mathrm{d}K/\mathrm{d}t = g(\bar{K} - K) - Z \tag{1}$$

where $\bar{K}$ is the ''natural'' level of environmental capital, Z is the flow of pollutants, and $g > 0$ measures the recovery rate of the environment.[5] Absent any pollution, in the long run environmental capital would gravitate towards its natural steady state at the pristine level $\bar{K}$. For example, we may think of Z as the average flow of sulphur oxides emitted per year, and K as a measure of average ambient air quality.

There are two industries denoted M and A. M, or Smokestack manufacturing, is a dirty industry that uses labor as an input and emits pollution as a joint product of output. We assume that one unit of labour can produce one unit of manufactures, and generates λ units of pollution:

$$M = L_{\mathrm{M}} \tag{2}$$

$$Z = \lambda L_{\mathrm{M}} \tag{3}$$

Our other industry, denoted by A, is an environmentally sensitive industry that

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[4] We omit time subscripts to economize on notation. All variables refer to current period values unless indicated otherwise.

[5] Admittedly our pollution dynamics are quite rudimentary. Nature's regeneration function is linear and purely compensatory with reductions in K bringing about compensating increases in nature's rate of regeneration $(\mathrm{d}K/\mathrm{d}t)/K$. In addition, our regeneration function assumes that there is no minimum viable level of the environment's capital stock since $\mathrm{d}K/\mathrm{d}t$ is still positive at $K = 0$. Moreover, since the flow of pollution emissions, Z, enters Eq. (1) linearly, the marginal physical damage of pollution to the environment is constant. These assumptions were chosen primarily to simplify the analysis and in Section 7 we consider the implications of two alternative specifications.

may be thought of as Farming.[6] Production of A uses labor as an input, but production is also dependent on the free flow of services (sun, rain, clean air and water, etc.) provided by the stock of environmental capital. Hence:

$$A = F(K)L_A \tag{4}$$

where L_A is labor allocated to agriculture and $F(K)$ is the flow of services arising from an environmental capital stock of K. For simplicity, we let $F(K) = K^{\varepsilon}$, with $0 < \varepsilon < 1$.[7]

Labour markets are competitive and labourers are freely and costlessly mobile across sectors. As a result, labour reallocates itself across sectors instantaneously ensuring that within a country, wages and marginal value products are always equalized when both sectors are active. This instantaneous adjustment in labour markets, coupled with our assumption of gradual adjustment of the environment's capital stock, simplifies the dynamic analysis considerably. Together these two assumptions primarily reflect our view that the speed of adjustment of the environmental processes involved are slow in relation to the usual equilibrating forces at work in market economies.

We assume a representative consumer with current period utility given by:

$$U = b_m \ln(M) + b_a \ln(A) \tag{5}$$

where b_m and b_a are the shares of spending on M and A. As noted above, to highlight the role of production externalities, we assume that environmental quality does not directly affect utility. Our main results do not require constant budget shares, nor homotheticity. The Mill–Graham assumption of constant budget shares has a long history in the trade and external economies literature (see Melvin, 1969; Ethier, 1982; Panagariya, 1981, etc.). Its primary usefulness lies in the ability to link primitives to the existence of certain types of Pareto ranked equilibria.

3. Autarky

We begin by considering the steady state properties of the model in autarky. Our primary motivation for considering autarky is to establish a benchmark showing

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[6] Our analysis applies to any two industries where one inflicts a negative production externality on the other. Farming may be a bit of a misnomer, because agriculture is a major source of nonpoint source pollution.

[7] Eq. (1) assumes that pollution creates a constant marginal physical damage to the stock of environmental capital K, but our assumption of $\varepsilon < 1$ in (4) ensures that equal reductions in K create increasingly large decreases in the productivity of clean good production. Holding prices and labour allocations fixed, our specification yields a typical increasing and convex marginal (economic) damage function.

that under our specification, the autarky equilibrium is unique and stable even though our economy's steady state production possibility frontier is strictly convex. Although multiple equilibria and instability are endemic to models where production externalities lead to nonconvexities, our assumptions rule out these complications in autarky. As a result, we are able to very clearly link free trade per se to the introduction of these complications.[8]

As a first step, we construct the economy's steady state production frontier to demonstrate that it is strictly convex throughout. Using (2) and (4), full employment of labor requires that at every point in time:

$$L = L_{\mathrm{M}} + L_{\mathrm{A}} = M + \frac{A}{K^{\varepsilon}} \tag{6}$$

This gives us an expression for the economy's short run production frontier. It is linear, reflecting the Ricardian structure of the economy in the short run. Points along such a frontier are not necessarily sustainable, however, since the environmental capital stock K in (6) is dependent on the economy's history of pollution discharge. Changes in M induce changes in pollution which in turn affect K. To obtain the steady state or sustainable production frontier, we use (3) and (2) in (1), and find that K evolves according to

$$\mathrm{d}K/\mathrm{d}t = g(\bar{K} - K) - \lambda M \tag{7}$$

A steady state corresponds to $\mathrm{d}K/\mathrm{d}t = 0$ in (7). Provided specialization in M will not result in destruction of the entire capital stock,[9] the steady state relationship between Smokestack output and environmental capital is then given by

$$K = \bar{K} - \lambda_{\mathrm{M}} M \tag{8}$$

where $\lambda_{\mathrm{M}} \equiv \lambda/g$. Using (8) to eliminate K in (6) and rearranging yields the steady state production frontier:

$$A = (L - M)(\bar{K} - \lambda_{\mathrm{M}} M)^{\varepsilon} \tag{9}$$

This function is strictly convex.

Not surprisingly, given our convex production frontier, the steady state supply curve for Smokestack output is negatively sloped over some range. To construct this supply curve consider first the conditions under which both sectors are active in steady state. For manufacturing, the zero profit condition requires, using (2):

$$p_{\mathrm{M}} = w \tag{10}$$

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[8] This is a common practice. Ethier (1982) imposes sufficient structure on preferences and technologies to render autarky a unique and stable equilibria for exactly these same reasons.

[9] That is, we assume that $\bar{K} - \lambda L/g > 0$. This will not affect the qualitative results.

Agricultural firms maximize profits, treating the environmental capital stock as given, and thus using (4), we must have:

$$p_a K^{\varepsilon} = w \tag{11}$$

Dividing (10) by (11) yields

$$\frac{p_M}{p_a} = K^{\varepsilon} \tag{12}$$

which tells us that at a point in time relative prices are determined by the environmental capital stock. Consequently, if both industries are active in steady state, then using (8) in (12), we have

$$p \equiv \frac{p_M}{p_a} = (\bar{K} - \lambda_M M)^{\varepsilon} \tag{13}$$

which is a decreasing function of M. If $p_M/p_a < (\bar{K} - \lambda_M M)^{\varepsilon}$, for any M, it is profitable to shift labor out of M and into A, and conversely, if $p_M/p_a > (\bar{K} - \lambda_M M)^{\varepsilon}$, the M industry expands and A contracts.

The supply curve for M is illustrated in Fig. 1 (and denoted ''S''). Along the locus of points described by (13), the economy produces both M and A. Notice

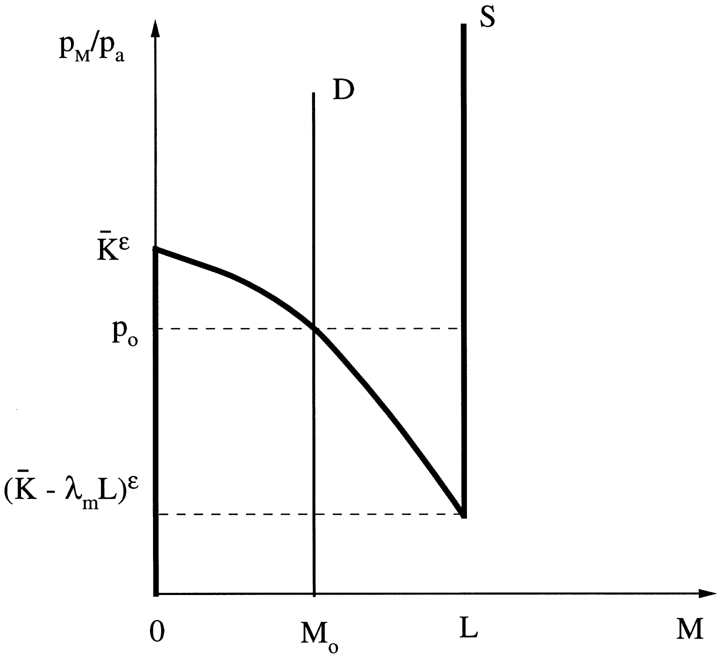

Fig. 1. Steady state demand and supply for manufactures.

that the supply curve slopes downward in this range: an increase in M results in a lower steady state environmental capital stock and lower productivity in agriculture. This reduces the demand for labor in agriculture and hence lowers the minimum price required to support the increased supply. The supply curve contains two other segments, corresponding to specialization in either M or A. For $p_M/p_a < \bar{K}^{\varepsilon}$, then for $M=0$, (13) is violated, it is profitable for A to expand, and the economy can specialize in A. Hence the vertical segment $[0, \bar{K}^{\varepsilon}]$ at $M=0$ lies on the supply curve. Finally, at $M=L$, the economy specializes in M. For $p_M/p_a > (\bar{K}-\lambda_M L)^{\varepsilon}$, it is profitable for M to expand, and consequently, the economy can specialize in M for any such price. This leads to the right hand vertical segment of the supply curve.

As is standard in models with convex production frontiers, supply is not unique over a range of prices and there may be multiple equilibria in autarky. Nevertheless, with sufficient restrictions on demand there is a unique equilibrium. With our Mill–Graham preferences, the demand for M is given by

$$D_M = \frac{b_M wL}{p_M} = b_M L \tag{14}$$

using (10). Hence the demand curve in autarky is vertical and we have:

Proposition 1. *A globally stable, unique steady state equilibrium exists in autarky.*

Proof. See Appendix A.

An alternative graphical method of proof is given in Fig. 2 (ignore for the moment the bold line labelled ‘‘Free trade pollution function’’). If we measure pollution flows and environmental cleansing on the vertical axis and K on the horizontal axis, then the environment’s cleansing function, $g(\bar{K}-K)$, can be illustrated by the downward sloping line in Fig. 2. As well, from (14) we know that the level of pollution emissions is independent of K and given by the ‘‘Autarky pollution function’’ $Z=\lambda M=\lambda b_M L$ shown in the figure. By construction a positive (negative) vertical distance between the cleansing function and the autarky pollution function implies that the stock of environmental capital must be growing (shrinking), and hence the unique steady state level of environmental capital is at $K=K_0$. Moreover as Fig. 2 makes clear, the unique steady state is globally stable and the adjustment of K towards its steady state value must be monotonic.

4. Free trade in a small open economy

We now consider trade. In autarky, domestic market conditions constrain the amount of pollution that the economy generates, and this in turn stabilizes the level of environmental capital. If Smokestack expands too much, farming output

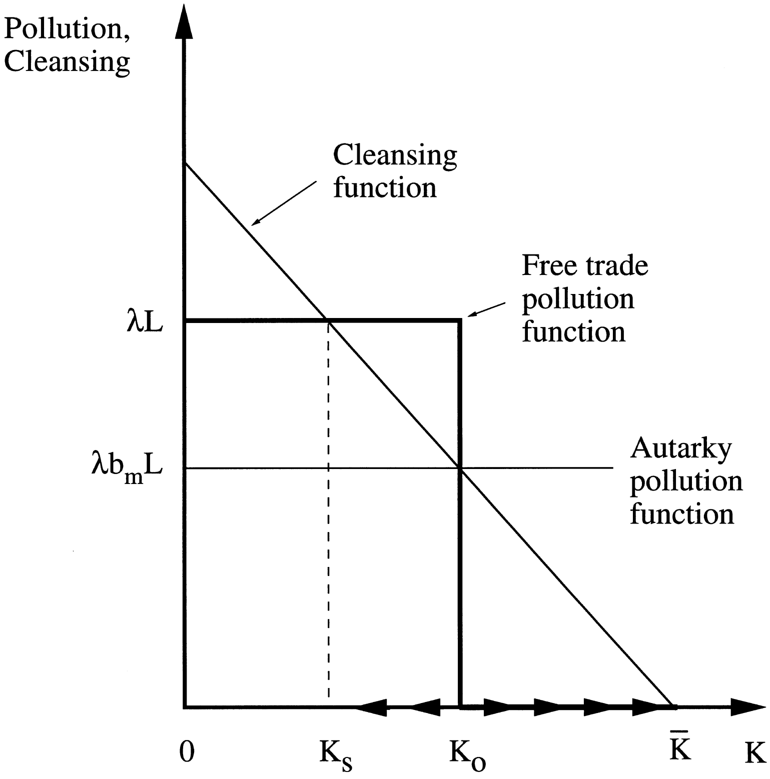

Fig. 2. Free trade for a small open economy.

becomes scarce, relative prices adjust, and market forces encourage smokestack to contract, thereby reducing pollution. Although there is still too much pollution because of the externality, the market for farming output acts as a restraint on pollution in autarky.

Trade can eliminate this market-driven check on the level of pollution. This is illustrated most effectively by considering a small price-taking economy that faces a world relative price p* equal to its autarky price p_o. The demand curve facing this small open economy is now perfectly elastic as shown by the dashed line at p_o in Fig. 1, and there are now three possible steady state equilibria in trade. These are illustrated in Fig. 1 and consist of the original autarky diversified equilibrium at M_o (with no trade) plus two additional equilibria where the economy is specialized in either A or M (with trade).

More significantly, the opportunity to trade has rendered the autarky equilibrium unstable. This can be illustrated with the aid of Fig. 3, which depicts a series of short run equilibria of the economy. The short run production frontier corresponding to the autarky steady state capital stock K_o is labelled in the figure as

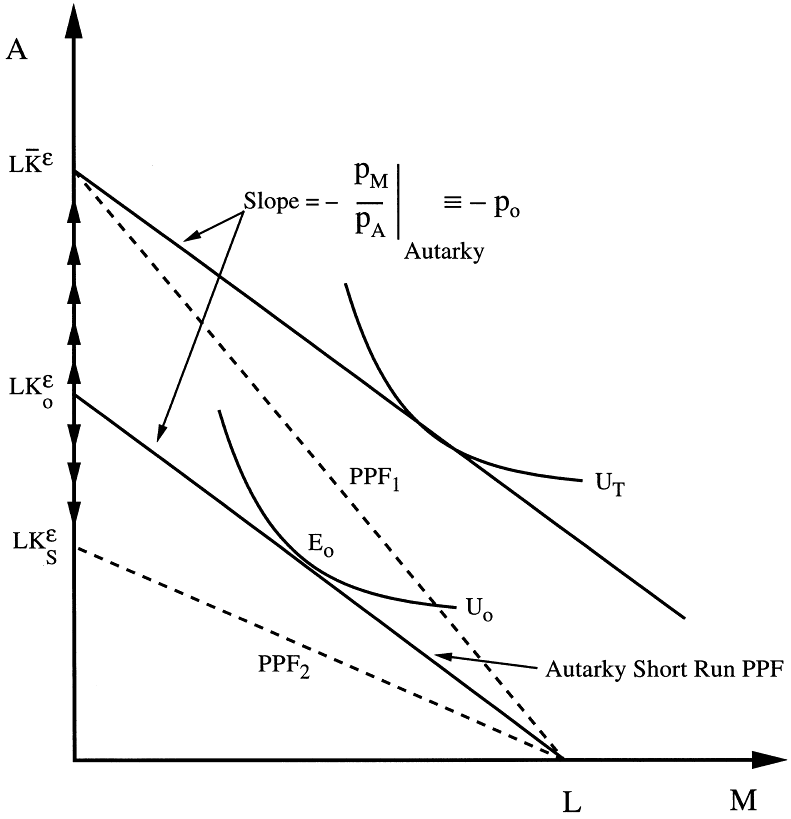

Fig. 3. Response of the short run production frontier to trade.

"Autarky Short Run PPF". For a given level of K, the production frontier is linear, and so in the short run, the model behaves like the simple Ricardian model. The autarky equilibrium is at point E_o, utility is U_o, and the autarky price ratio is p_o. Now suppose that the economy opens up to trade at a fixed world price equal to the autarky price ratio. To see that the autarky equilibrium is unstable, suppose that the economy deviates slightly away from point E_o and that production of M increases. This will lead to more pollution, and hence from Fig. 2, we know that environmental capital K will start to fall. But as K falls, productivity in sector A is reduced, and so the short production frontier starts to rotate downward (as indicated by the arrows on the A axis in Fig. 3). In autarky, prices would adjust, pollution would drop, and the economy would gradually return to point E_o. But in free trade, prices do not adjust, since they are now fixed in world markets. Consequently, as the PPF rotates downward, it becomes flatter than the world price ratio, and so the economy develops a comparative advantage in Manufacturing.

With a linear production frontier, this leads the economy to specialize in M, and so pollution rises. But this reinforces the initial movement away from point E_o, as K falls even more, causing a further flattening of the production frontier, and a strengthening of the comparative advantage in the polluting industry. A similar argument can be used to show that a slight *increase* in K will also be reinforced, leading the economy to specialize in sector A. Consequently, the autarky equilibrium is unstable in free trade.

The new possible steady states can be determined by constructing the free trade pollution function as illustrated in Fig. 2. As discussed above, in free trade (with $p^* = p_o$), a slight drop in K leads the economy to specialize in M. Consequently from Eq. (3), pollution rises to $Z = \lambda L$ for all $K < K_o$. This is illustrated by the left half of the heavy dark line in Fig. 2. On the other hand, if K rises above K_o, then the economy specializes in A, with pollution dropping to zero. Thus the free trade pollution function steps down to $Z = 0$ for $K > K_o$ (the right half of the heavy dark line in Fig. 3). Finally, at $K = K_o$, production is indeterminate, since the short run production frontier has the same slope as the world price ratio. Consequently, the free trade pollution function is vertical at $K = K_o$.

Combining the free trade pollution function with the environment's cleansing function, we can see from Fig. 2 that the three possible steady states are at K_s, K_o, or $\bar{K}$, with K_o being unstable. With this construct in hand, it is straightforward to prove:

Proposition 2. *If trade occurs at fixed world prices equal to autarky prices, there are three possible steady state equilibria. Only the two specialized equilibria are stable; the diversified autarky equilibrium is unstable.*

Proof. See Appendix A.

Proposition 2 bears a strong resemblance to similar results in the trade and increasing returns literature. Its importance lies not in illustrating the theoretical possibility of instability, but rather in linking free trade with a cumulative process of environmental change begetting industrial restructuring that in turn begets further environmental change. A slight expansion in Manufacturing output creates a comparative advantage in M, which increases the output of M. This generates yet more pollution, which further degrades K, and reinforces the newly-created comparative advantage in M. This process of cumulative causation locks the country into a high-pollution, low-environmental-capital steady state. Conversely, if manufacturing output were to decline slightly below M_o, then the relative productivity of A rises, and a similar process would lead the economy to specialize in farming.

While trade at autarky prices leaves us with two possible trading equilibria, trade at just above or below autarky prices leaves us with more determinate results. If the world relative price of M is slightly below the autarky price, then at the outset of trade, the economy will unambiguously specialize in farming even at the initial level of $K=K_o$. In terms of Fig. 2, the vertical segment of the free trade pollution function is to the left of the one shown in Fig. 2. Consequently, the economy will evolve towards the steady state $K=\bar{K}$. Alternatively, if the price of M is slightly above the autarky price, then at the outset of trade the economy will specialize in smokestack. The vertical segment of the free trade pollution function will be to the right of the one shown in Fig. 2, and the steady state equilibrium will be at K_s.

Trade occurs in this model because it leads to a separation between the location of consumption and the location of production. With cross-industry externalities, such separation affects relative productivities and creates comparative advantage. Environmentalists have often made the point that trade can be harmful for the environment precisely because it separates the location of consumption from the location of production (see Daly, 1993, p. 57). The argument is that trade allows consumers of pollution intensive goods to escape the direct negative environmental consequences of their consumption. However, in a world with pure production externalities, the concentration of environmental destruction may well be desirable. In fact, with no direct disutility cost of pollution, free trade is always welfare improving in our small open economy model, despite the absence of pollution policy.

Proposition 3. *Free trade is welfare improving for a small open economy.*

Proof. See Appendix A.

This result can be illustrated with the aid of Fig. 3 for the case where the free trade price ratio is equal to autarky prices. If the economy specializes in farming, then trade leads to a regeneration of the stock of environmental capital, causing the short run production frontier to rotate upward to PPF_1. Consequently, free trade utility U_T is clearly above autarky utility U_0. Note that there are no static gains from trade, but there are dynamic gains. On the other hand, if the economy specializes in manufacturing, then the production point moves to L. Although the production frontier rotates downward, this does not reduce utility, because environmental capital is not used in the production of M. In this case, free trade utility is the same as in autarky. Finally, note that if the world price ratio is different than the autarky price ratio, then the gains from trade would be larger, as there would be standard static gains from trade in addition to the dynamic effects discussed above.

Once we introduce some complexities into the model, the benefits of separating industries must be weighed against potentially offsetting factors. For example, if relative prices can adjust along the transition path, then a country may end up ‘‘trapped’’ in an industry that at current world prices leaves it with lower real income than before trade.[10] We consider this and related issues in the following sections.

5. Trade in a two country world

We now consider trade between two countries, Home and Foreign. Foreign variables are denoted with an asterisk (‘‘*’’). To abstract from all other motives for trade, we start by assuming the countries are identical prior to trade: they have the same technology, labour supplies and environmental cleansing functions. Identical countries have identical stocks of environmental capital and identical relative prices in autarky. Consequently, autarky is a free trade equilibrium. This equilibrium is unstable, however, since any increase in Smokestack output by one country initiates a self-reinforcing cycle of pollution-induced declines in agricultural productivity, and increased comparative advantage in the Smokestack industry. Thus trade can emerge between two identical countries.

The standard explanation for trade between similar countries is based on increasing returns to scale. With increasing returns, there is an incentive for an industry to concentrate in one location to reap the benefits of positive external economies. Negative externalities across sectors provide an alternative, but closely related, motive for trade arising from the beneficial separation of incompatible industries. The analytics are closely related because of a symmetry imposed by general equilibrium resource constraints.

To see how this symmetry between external increasing returns in one sector and a cross-industry negative externality arises, suppose primary factors move into Farming. Moving factors into Farming means drawing them from Smokestack. Smokestack pollution falls, the environment improves, and this increases the productivity of primary factors in Farming. Note that the same beneficial increase in Farming’s productivity could have arisen had we assumed Farming had external increasing returns linked to its output level. A consequence of this symmetry is that some of the intuition for our results is similar to Ethier (1982), but the parallels are not exact as we show in Section 6.

Given the Ricardian structure of the model there are three possible types of trading steady states. We consider each in turn below. In addition since we are starting with identical countries, there are always two symmetric equilibria of each type. For concreteness, in the following we will always associate Home with the

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[10] As well, if the short run production frontier is concave, then the economy will not specialize completely in free trade, and so when the economy has a comparative advantage in M, the deterioration of environmental capital will be welfare-relevant. And if environmental quality enters directly into the utility function, then the welfare results must also be modified in an obvious way.

country that produces farm output and can in some cases be entirely specialized in farming.

5.1. High demand for the dirty good

Provided the demand for smokestack output is ‘‘high’’, both countries must produce Smokestack in any trading equilibrium. In our model a ‘‘high’’ demand corresponds to $b_m > 1/2$. This ensures that Foreign specializes in *M*, while Home produces both goods. In this case, wages must be equal across countries, and both countries will gain from trade.

The transition from autarky to the trading steady state is illustrated in Fig. 4. In autarky, both countries have K_o units of environmental capital and produce both goods. With the opening of trade, this no-trade equilibrium becomes unstable. Suppose Foreign output of *M* rises. This increases pollution, lowers K^*, and gives Foreign a comparative advantage in *M*. If the demand for Smokestack is high, then

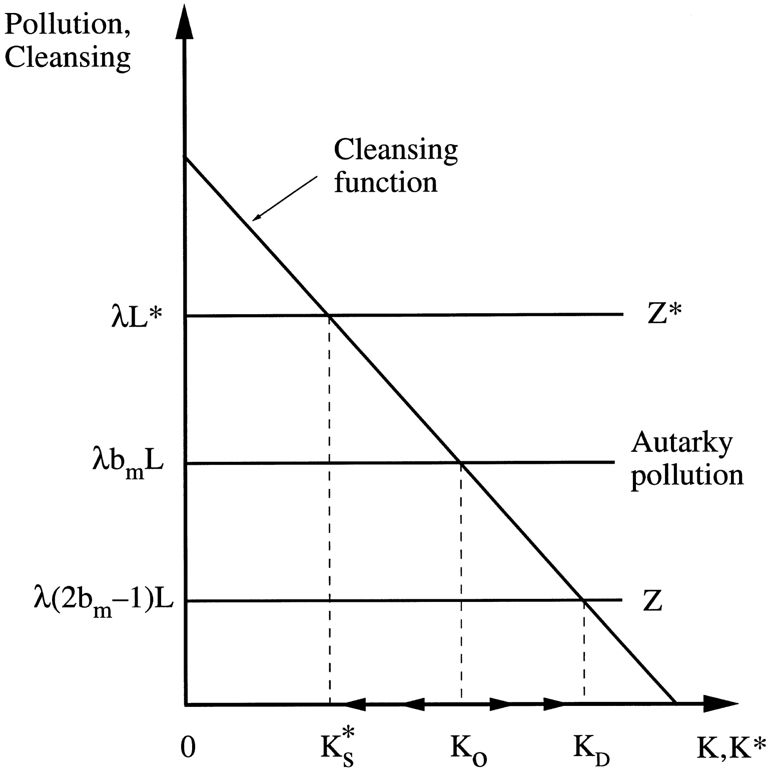

Fig. 4. High demand for Smokestack: Transition dynamics to a diversified steady state.

Foreign must specialize in M. Foreign's pollution level shifts up to $Z^*=\lambda L^*$ as shown, and its stock of environmental capital falls toward K_s^*, reinforcing its comparative advantage in M. Moreover, it is apparent from the figure that the adjustment of K towards its steady state is monotonic and that the steady state at K_s^* is stable.

At the same time, when Home begins to import Smokestack its output of M falls. As long as Smokestack is produced in both countries, wages must be equalized across countries ($w=w^*=p_m$), and recalling (14), the world demand for M is given by

$$M^w = b_m(wL + w^*L^*)/p_m = b_m(L + L^*)$$

Because Foreign produces L^* units of Smokestack when specialized, Home produces $M=M^w-L^*$ units. As a result, Home's flow of pollution in trade becomes

$$Z = \lambda M = \lambda[M^w - L^*] = \lambda[b_m(L + L^*) - L^*] = \lambda(2b_m - 1)L$$

since $L=L^*$. This new pollution level is shown in Fig. 4, and is positive if $b_m>1/2$. Since this flow of pollution is less than its autarky level, Home's stock of environmental capital begins to recover and it gradually moves toward its diversified steady state value at K_D. Moreover, it is apparent from the figure that the adjustment of K^* towards its steady state is monotonic and that the steady state at K_D is stable. More formally,

Proposition 4. *If* $b_m>1/2$, *then in the only stable steady state, trade emerges between two ex ante identical countries. Both countries produce Smokestack but only one country produces Farm output. Both countries gain from trade.*

Proof. See Appendix A.

While the effects of trade on the environment are very different across countries, both countries must gain from trade. Home gains from the increase in its production possibilities created by its improving environment, and Foreign gains from the terms of trade improvement brought about as the relative price of A falls in response to improved productivity in Home. This can be illustrated by referring to Fig. 3 once again. Home's production frontier rotates upward after free trade (although in this case not quite as far up as in the diagram since K evolves to $K_D<\bar{K}$). But since Home remains diversified in free trade, world prices must also adjust so that the world relative price of M remains equal to the slope of Home's production frontier. Consequently, p_M/p_A rises with trade. Since foreign exports M, this means that the Foreign terms of trade gradually improve as the economy adjusts to the new free trade steady state. Although foreign production remains at point L, it gains as its budget constraint rotates upward with the increase in p_M/p_A.

In this case, trade serves as an imperfect substitute for environmental policy.

Because of the negative production externality, it is efficient to separate the two industries. International trade provides incentives for this separation to occur in a free market.[11] Separation per se is not, however, sufficient for trade to always benefit both countries. As we show below, when Smokestack is concentrated in one country alone, separation is almost complete, but the gains from this separation are not equally shared across countries. In fact, one country must lose from trade.

5.2. High demand for the clean good

Now consider the case where there is a relatively strong demand for the clean good ($b_a > 1/2$ or equivalently, $b_m < 1/2$). Two types of equilibria may emerge, depending on the strength of this demand. If b_a is sufficiently large, then both countries must produce *A* in the steady state. On the other hand, for intermediate values of b_a, both countries may be specialized in production. In either case, all of the manufacturing is concentrated in one country. As a result, wages need not be equalized across countries in free trade.

As before, the autarky allocation is an unstable free trade equilibrium, since any deviation in production patterns initiates a dynamic process that generates and reinforces comparative advantage. To analyze the adjustment path to the free trade steady state, suppose that Foreign deviates slightly from its autarky output levels and increases its output of *M* with the opening of trade. The ensuing pollution-created fall in K^* gives Foreign a comparative advantage in *M* and Home a comparative advantage in *A*. With a high demand for *A*, Home specializes in *A*. Foreign produces all of the world's *M*, but with K^* only marginally less than *K*, and with $b_a > 1/2$, Foreign must also produce some *A*.[12] Hence, at least in the early stages of adjustment, the Foreign country produces both goods, while Home is specialized in *A*. As we shall see, during the transition to the trading steady state Foreign could either remain diversified in production, or if the demand for Smokestack is sufficiently high, it may be driven to specialize. Home, on the other hand, must remain specialized.

Let us first consider the case where Foreign remains diversified in the steady state (b_a is large). The adjustment path is illustrated in Fig. 5(a), where we have plotted the regeneration function (1) and some pollution functions for the Foreign country, which we denote by Ω_i.[13]

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[11] Notice, however, that the equilibrium is not Pareto efficient: because of the externality, there will still be excessive production of *M* in the country that produces both goods.

[12] To prove this result note that when $K = K^*$, world labour demand in *M* is $2b_m L < L$ since $b_m < 1/2$ (see $\Omega(K, K^*)$ below). Hence for *K* near K^*, Foreign must diversify.

[13] An equivalent, but quite cumbersome, analysis using phase plane techniques is available on request from the authors.

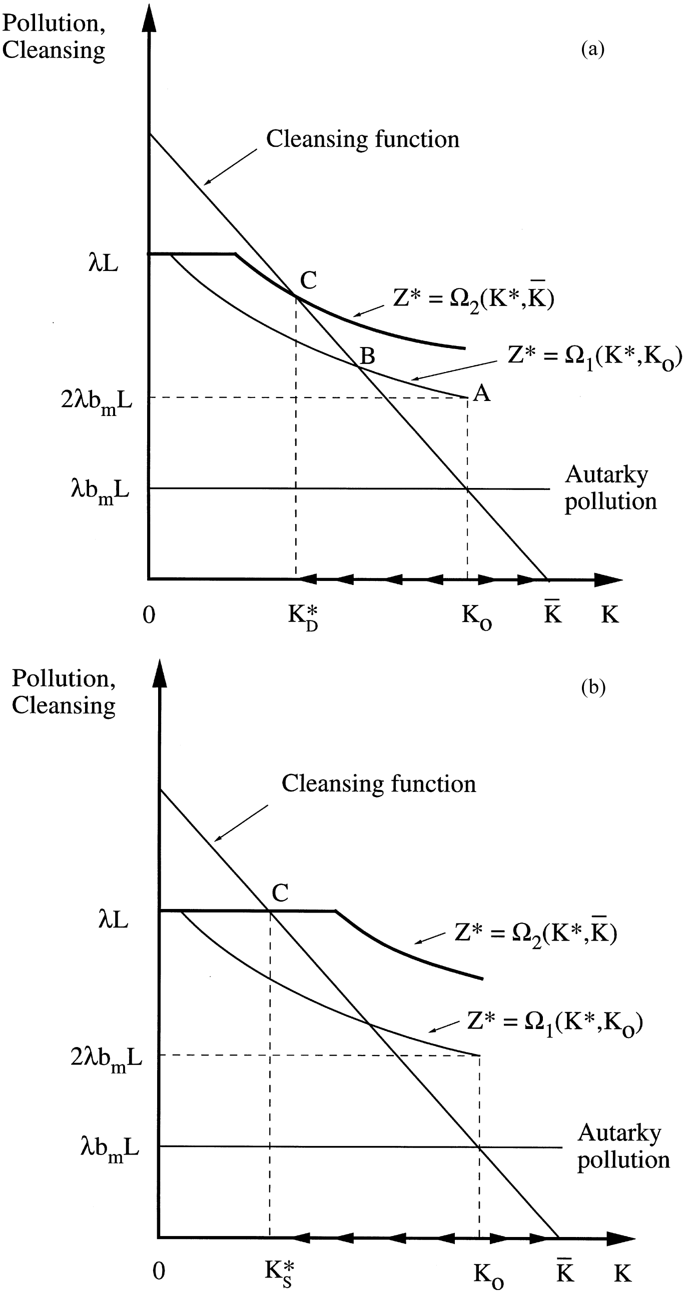

Fig. 5. (a) High demand for Agriculture: Transition dynamics to a diversified steady state. (b) High demand for Agriculture: Transition dynamics to a fully specialized steady state.

The pollution function Ω gives the level of pollution generated by Foreign as a function of the current level of K and K^*. Foreign pollution is a by-product of its manufacturing output, and since Home is specialized in A, Foreign must satisfy the world demand for M, which is

$$M^{\mathrm{W}} = b_{\mathrm{m}}(w^*L^* + wL)/w^* \tag{15}$$

To eliminate wages from (15), note that as long as both countries produce A, unit production costs must be equal across countries. This requires:

$$p_{\mathrm{a}} = w/K^{\varepsilon} = w^*/K^{*\varepsilon} \tag{16}$$

Using (16) in (15), and recalling that pollution is $Z^* = \lambda M^*$, yields an expression for the foreign pollution function when production is diversified:

$$\Omega(K, K^*) = \lambda b_{\mathrm{m}}(L^* + LK^{\varepsilon}/K^{*\varepsilon})$$

For given K, $\Omega(K^*; K)$ is a convex decreasing function of K^*. The intuition is straightforward. If K^* falls, Foreign productivity in A decreases. From (16), Home's wage (and hence the relative price of the clean good) must rise so that unit costs remain equal across countries. With a higher income created by a beneficial terms of trade effect, Home's demand for manufactures ($b_{\mathrm{m}}wL/w^*$) must rise, thus increasing Foreign pollution. Foreign demand for manufactures, however, remains fixed at $b_{\mathrm{m}}w^*L^*/w^* = b_{\mathrm{m}}L^*$. Consequently, the world's derived demand for Foreign pollution rises as K^* falls.

On the other hand, Ω is *increasing* in K. As K rises, Home's real wage rises, thus increasing its demand for foreign-produced M. This stimulates the Smokestack industry and increases Foreign pollution. Thus an increase in K in the Home country shifts up the Ω curve in Fig. 5(a).

Finally, we must note that Foreign pollution is bounded above by the possibility that it may eventually specialize in M. If Foreign specializes in M, then its pollution is $Z^* = \lambda L^*$. Thus, taking this into account, Foreign pollution in trade is given by:

$$Z^* = \mathrm{Min}[\lambda L^*, \Omega(K^*; K)]$$

One such pollution function is shown in Fig. 5(a) by the bold line.

With this apparatus in hand consider the transition to free trade. At the outset of trade Home specializes in A, Smokestack shuts down, and $Z = 0$. Home's pollution function becomes coincident with the horizontal axis in Fig. 5(a), and its environmental capital stock begins to recover. Over time it approaches $\bar{K}$. In contrast, when Home specializes in agriculture, Foreign initially doubles its manufacturing output. Consequently, foreign emissions jump to point A on $\Omega_1(K^*; K_{\mathrm{o}})$. Since foreign pollution is now higher than the natural regeneration rate, its environmental capital K^* starts to fall.

Over time, Foreign pollution rises for two reasons. First, as K^* falls, Home's terms of trade improve. This creates an increase in Home demand for Smokestack, while Foreign's own demand for Smokestack is fixed at $b_m L^*$ because Foreign is diversified during this process. Consequently, world demand for Smokestack rises, as does the world's derived demand for Foreign pollution. In Fig. 5(a), this corresponds to a movement along $Z^* = \Omega_1(K^*;\ K_o)$ towards point B. Second, Home's environmental capital K rises throughout the transition. This induces an increase in Home's real income that further raises Home's derived demand for Foreign pollution. In Fig. 5(a), this is captured by continual upward shifts of $\Omega(K^*;\ K)$ over time.

If the demand for the clean good is very strong, then Home cannot satisfy the entire world demand, and Foreign must remain diversified in the steady state. This is the case illustrated in Fig. 5(a). Foreign's steady state pollution function is $\Omega_2(K^*;\ \bar{K})$, and there is a stable steady state equilibrium at point C with $K^* = K^*_D$.[14] Foreign produces both goods, and Home is specialized in A. Although the two countries are initially identical, their welfare outcomes diverge with trade: Home must gain, and Foreign must lose.

Proposition 5. *There exists some* $\underline{b} < 1/2$ *such that if* $b_m < \underline{b}$, *then in free trade Home specializes in Agriculture and Foreign diversifies. There are no static gains from trade, but Home experiences dynamic gains from trade, while Foreign suffers dynamic losses.*

Proof. See Appendix A.

This can be illustrated with the aid of Fig. 3. Because Foreign output of M rises with trade, its production frontier begins to rotate downward. And because it is still producing some farm output, the fall in the production frontier reduces real foreign income for given prices. Moreover, since Foreign must remain diversified, the world relative price of M must adjust so that it remains equal to the slope of the foreign production frontier. Hence p_M/p_A must fall during the transition. Since Foreign exports M, this means that Foreign terms of trade deteriorate, further reinforcing its losses from trade. On the other hand, this terms of trade deterioration for Foreign is a terms of trade improvement for Home. This raises Home's demand for Foreign manufactures, leading to yet more foreign pollution. The foreign environment worsens, productivity in the clean sector falls, and the

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[14] Since $\Omega_2(K^*;\ \bar{K})$ is convex, there could be multiple diversified equilibria in the Foreign country, but only the equilibrium with the largest K^* is stable. It is also possible that there may exist both diversified and specialized equilibria for Foreign for given b_a. However, during an adjustment from autarky to free trade as described above, the economy converges to the diversified equilibrium described above. For more details, see the unpublished notes referred to in footnote 13.

entire cycle of environmental degradation and terms of trade deterioration repeats and reinforces itself over time.

The contrast between Propositions 4 and 5 is striking. Trade is mutually beneficial only when the demand for the dirty good is sufficiently strong. With a strong demand for the clean good, one country must lose from trade even though trade still provides efficiency gains by separating incompatible industries. Foreign losses accrue from mutually reinforcing sources. Foreign loses because when it raises Smokestack output, it degrades its environment and lowers the world supply of Farm output (its import good). As a result, Foreign suffers from a deterioration in its terms of trade as a direct consequence of its own environmental degradation!

There are several important points to note about this possibility of losses from trade. First, the key to Foreign losing from trade is the negative terms of trade effect created by its own environmental degradation. Thus Propositions 3 and 5 are not inconsistent. If the terms of trade were held constant, Foreign would immediately specialize in Smokestack (and remain specialized) when it degrades its environment. As discussed in Section 4, depletion of its environmental capital in this case is essentially irrelevant to foreign welfare. Only when world prices adjust in response to changes in K and K^* does Foreign potentially lose from trade.

Second, it is striking that losses from trade only occur if the demand for the clean good is sufficiently high. As well, from our diagrammatic account it is apparent that losses from trade are more likely when the environment's regeneration rate, g, is high, and when the externality is relatively weak (ε is low). An increase in g shifts the cleansing function $g(\bar{K}-K^*)$ outwards making a diversified equilibria with losses from trade more likely. If ε is small, then Foreign's pollution function is almost a flat line for any given K; moreover, if ε is small then the shift upwards in the pollution function is smaller. Consequently, for both reasons, the smaller is ε the greater the possibility of diversification and losses.[15]

These seemingly inexplicable results are not without reason. When Foreign has a greater regeneration rate, any increase in Smokestack pollution leads to a smaller reduction in environmental capital. Consequently, Foreign's terms of trade deteriorate less from an increase in pollution, and Home gains less from the change in world relative prices brought about by Foreign's environmental degradation. As a result, Home's demand for Smokestack is less, and this makes diversification (and losses) more likely for Foreign.

As well, if e is small then the pollution-induced decline in the output of the clean good is relatively small. Again, the induced terms of trade effect is small,

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[15] This does not imply that the losses from trade are greater when ε is small. We suspect that just the opposite is true: when ε is small a diversified equilibrium is more likely, but the losses from trade are smaller too. Note when $\varepsilon=0$ there can be no losses (or gains) from trade.

and the attendant increase in the demand for Smokestack by Home is smaller as well. Consequently, diversification and losses for Foreign are more likely again.

5.3. Both countries specialized

Finally, we consider the intermediate case where both countries specialize in the steady state. This occurs when $\underline{b}<b_m<1/2$: the demand for Smokestack is stronger than in the previous case, but not as strong as in part *A* of this section.

This possibility is illustrated in Fig. 5(b). In the steady state, Foreign's free trade pollution function is $\Omega_2(K^*; \underline{K})$ and the steady state equilibrium is at point C. Because of the relatively stronger demand for Smokestack during the transition, the foreign pollution function Ω eventually rises everywhere above the regeneration function. Consequently, Foreign specializes in Smokestack in the steady state.

The possibility of specialization has important welfare implications for the Foreign country. The time path of foreign welfare is not monotonic during the transition: it first falls, and later rises. In the early part of the transition, Foreign is diversified in production, and its welfare falls as shown above. But once Foreign specializes, further depletion of its own environmental capital becomes economically irrelevant, and moreover, Foreign (an importer of *A*) now benefits from a terms of trade improvement as Home's production of *A* rises over time.[16] A Foreign worker's real wage in terms of manufactures is constant throughout, but his or her real wage in terms of *A* starts to rise once the country specializes. To see this, note that once both are specialized, zero profits in each country requires $p_m=w^*$, and $p_A=w/K^{\varepsilon}$. Hence,

$$\frac{p_m}{p_A}=\frac{w^*K^{\varepsilon}}{w}=\frac{b_m LK^{\varepsilon}}{L^*(1-b_m)}$$

where the last step uses the market clearing condition for *M*.[17] Thus once Foreign is specialized, its terms of trade begins to improve as *K* continues to rise at home, and foreign welfare begins to rise. Whether or not Foreign experiences a net gain or loss from trade depends on its discount rate and on the speed with which it specializes in *M*.

On the other hand, Home must always gain from trade in this case. As shown above, it gains while Foreign is diversified. It must continue to gain when Foreign

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[16] Home's environmental capital stock approaches its steady state value as t goes to infinity. Foreign specializes, if at all, in finite time. For more details, see the unpublished notes referred to in footnote 13.

[17] The market clearing condition for *M* when Foreign is specialized is just $b_m(wL+w^*L^*)/p_m=L^*$, which implies $w^*/w=b_mL/L^*(1-b_m)$.

specializes because its real wage in terms of Farm output continues to rise.[18] Summarizing,

Proposition 6. *If* $b_m < 1/2$, *and a diversified steady state does not exist* (*other than the unstable no-trade steady state*), *then both countries must specialize in production. Home* (*specialized in A*) *must gain from trade at every point during the transition. Foreign utility initially falls, and later rises during the transition from autarky to free trade.*

Proof. See Appendix A.

6. Comparative advantage and the allocation of activities across countries

Thus far we have abstracted from differences across countries that could create a comparative advantage basis for trade. Pollution-created nonconvexities will however interact with the more conventional determinants of trade in any world with nonidentical countries. We concentrate on two key differences that are prominent in the literature: differences in assimilative/regenerative capacity (g vs. g^*), and differences across countries in population density (L vs L^*). Apart from examining how other determinants of comparative advantage may interact in our setting, we will show that once we admit nonidentical countries free trade may now lock-in the ‘‘wrong’’ pattern of specialization across countries.

Suppose $g > g^*$, but countries are otherwise identical. Then the environment in Home has a uniformly faster rate of regeneration (perhaps because of prevailing weather patterns, proximity to oceans, or physical differences in the soil, etc.) In autarky, we have $K > K^*$ and Home has a lower relative price of the clean good. At the outset of trade Home will increase its output of A while Foreign increases its output of M. If $b_m > 1/2$, then both countries must produce manufactures in trade: Foreign specializes in M while Home produces both goods.[19] If $b_m < 1/2$, then Foreign produces Smokestack and perhaps some Farm output, Home specializes in Farming. Note that Home must always gain from trade, while Foreign could lose from trade when $b_m < 1/2$.

Because externalities are not internalized, allocations before and after free trade will not be Pareto efficient. Nevertheless, we can ask whether, given this market failure, the market-determined pattern of trade is the same as that which a global central planner would choose.

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[18] From the zero profit condition at home, $w/p_a = K^{\varepsilon}$, which rises with K. For purchasing power in terms of M, note that from the previous footnote, $w/p_m = w/w^* = L^*(1-b_m)/Lb_m > 1$ since $b_m < 1/2$ and $L = L^*$. Recall that in autarky $w/p_m = 1$. Hence Home unambiguously gains from trade.

[19] The proof in footnote 12 also applies here because it does not rely on $g = g^*$.

In the present example, if one country must be diversified, a central planner would choose to locate the pollution intensive industry in the country with the higher environmental regeneration rate. This is because the higher ‘‘g’’ country can produce more Farm output for any given level of Smokestack since its regeneration rate is greater. If Smokestack demand is so high that it must be produced by both countries, then Foreign should specialize in Smokestack while Home diversifies. This is in fact the pattern of trade predicted when $b_m > 1/2$, and hence free trade allocates activities efficiently in this case.

But if $b_m < 1/2$, and full specialization does not occur, then Foreign is diversified while Home is specialized in A. The resulting pattern of trade is inefficient. If we forced Foreign to specialize in A and let Home diversify, then world output would be higher.[20] Consequently, we have shown:

Proposition 7. *The country with the faster rate of regeneration has the lowest autarky price of the clean good, exports the clean good in free trade, and always gains from trade. The direction of trade is efficient if* $b_m > 1/2$, *or if full specialization occurs. It will be inefficient for* b_m *sufficiently small.*

Now suppose $L^* > L$, but countries are otherwise identical. In autarky, we have $K > K^*$ and the less densely populated country has a comparative advantage in the clean good. At the outset of trade, Home increases its output of A while Foreign increases its output of M. If b_m is sufficiently large, then both countries must produce manufactures in trade: Foreign specializes in Smokestack while Home produces both goods. If b_m is sufficiently small, then both countries must produce A: Home specializes in A while Foreign diversifies. Home must always gain from trade, while Foreign can lose if b_m is sufficiently small.

For the direction of trade to be efficient, the smallest number of workers in the clean sector should be subject to the productivity-reducing effects of Smokestack pollution. Hence when the demand for Smokestack is high enough that both countries must produce it, a planner would choose Foreign (the more populated country) to specialize in Smokestack and Home to be diversified, since this minimizes the number of workers in the clean sector who have their productivity reduced. This is in fact the pattern of specialization created by trade.

When the demand for Smokestack is low (the demand for the clean good is high) it should only be produced in the less populated country (Home) to minimize the number of workers in the clean industry that are disadvantaged by Smokestack's productivity reducing effects. This is opposite to the pattern of trade that occurs in a free market. Hence we have:

Proposition 8. *The more densely populated country has the lowest autarky price*

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[20] Note, however, that a transfer may be required to ensure a Pareto improvement.

of the dirty good and will export it in free trade. The less densely populated country always gains from trade, the more densely populated country can lose when b_m *is sufficiently low. The direction of trade is efficient if* $b_m > L^*/(L+L^*)$*, and will be inefficient if* b_m *is sufficiently low.*

Proof. See Appendix A.

Both Propositions 7 and 8 show that trade need not lead to an efficient trade pattern. This is in sharp contrast to Ethier (1982) where free trade leads to an efficient pattern of specialization across countries. The reason is straightforward: concentration and separation are not equivalent, except in the sole case where both countries specialize completely. If we concentrate all of Smokestack in one country, we have not completely separated Smokestack from the environmentally sensitive industry. Since the productivity effects induced by trade arise from separation in our case, (and not concentration as in Ethier, 1982), our results differ.

For example, in an external economies model like Ethier (1982), whenever the demand for the increasing returns (IRS) good is low so that the IRS industry can fit into the smallest country, then it doesn't matter whether the larger or smaller country produces all of the IRS good. The logic is simply that there are benefits to concentrating IRS production in one country, but the concentration is complete if either of the two countries produces all of the IRS good. In contrast, when the demand for Smokestack is low so that Smokestack can fit inside the smallest country, efficiency is not met by either country taking all of the dirty industry production. Alternatively, when the demand for Farm output is so low that Farming can fit inside the smallest country, efficiency is again not met by either country taking all of the clean industry production. In both cases, because Smokestack affects the productivity of those workers remaining in the clean industry, it now matters which country gets the Smokestack industry.

7. Extensions and qualifications

The model we constructed in Section 3 was designed to illustrate as cleanly as possible the role that cross-sectoral externalities can play in generating trade and the role of terms of trade effects in distributing the gains from such trade across countries. While this stripped down model was useful to illustrate our basic point, its simplicity may belie important qualifications. Here we briefly consider some limitations of our analysis and report on their likely significance to the main results.

A simplifying assumption of our model was that each country consisted of only one region so that Smokestack and the environmentally sensitive industry could not separate geographically within a country. Clearly for large countries this form of domestic separation is possible in practice, although its feasibility is dependent on both the exact form of pollution emitted by Smokestack and by the mobility of factors across regions. If we maintain our 1 factor model, assume perfect mobility of labour, and introduce two regions within a country (each with their own environmental sink), then industries will separate across regions in autarky and free trade will provide no additional service in separating incompatible industries. Free trade at autarky prices will be a stable equilibrium and no trade will occur at these prices.

Alternatively, if there is zero factor mobility and two regions within a country, then there will be some spatial separation across regions in autarky but it is now limited by the immobility of factors across regions. In this context, trade can again play a role in separating incompatible industries much as described in our earlier sections. Hence the degree of internal factor mobility is a key determinant of whether international trade can play a useful role in separating incompatible industries.

In reality many environmentally sensitive industries are likely to be tied geographically by the location of specific factors. Tourism is tied to lakes, trees and mountains; fishing to streams and coastal areas. Unfortunately perhaps, forestry, pulp and paper, electricity generation and many other heavy industries are also tied to these same specific factors (trees, streams, rivers and access to water). Since many of these specific factors are highly concentrated geographically, then so too will be incompatible industries. As a result, free trade can again provide for further spatial separation and the logic of our model follows as before.

Another simplifying assumption was our choice of a one-factor model. While the Ricardian nature of the model at each point in time brings strong tendencies towards specialization, it is important not to attribute too much to this assumption. Our results rely most heavily on the nonconvexity introduced by cross-industry externalities. If we were to add more factors and let the industries differ in factor intensities, then there would be two forces at work determining the steady state production possibility frontier. The cross-industry externality tends to make the frontier bowed in to the origin while differences in factor intensities work in just the opposite direction. Our very simple steady state production frontier that was uniformly convex to the origin would be replaced by one with alternating concave and convex segments. If the autarky equilibrium occurred in a region where marginal rates of transformation were declining, then free trade at autarky prices would again be an unstable equilibrium. Free trade at autarky prices would again bring very large environmental consequences, although it would not bring about full specialization as in our Ricardian formulation. Consequently, we view the 1 factor assumption as a useful vehicle for illustrating our main points, but it is not wholly responsible for our results.

Third, our specification of the accumulation equation for environmental capital is clearly quite restrictive. For example, nature’s cleansing function exhibits the property that its rate of cleansing is higher the lower is the level of environmental capital. This type of ‘‘compensatory’’ growth function is often adopted in the renewable resources literature, but it rules out certain catastrophic outcomes that may arise when the quality of the environment falls below some minimum threshold. As well, our damage function is simply linear in the level of pollution emitted whereas the marginal physical damage from pollution may well be increasing in pollution levels. Burrows (1986) notes that the specification of the cross-sectoral externality will affect the likelihood of relevant nonconvexities in the production set. Here we consider two modifications to the accumulation equation.

First, if we replace our simple linear specification in Z with a convex and increasing damage function $h(Z)$ then very little of our analysis changes. In Fig. 2, the free trade and autarky pollution functions are still independent of the environment's capital stock and are just vertical translates of those shown. In the remaining figures similar adjustments need to be made, but since we only exploit the first derivative properties of our pollution functions the qualitative results of our analysis are unchanged by the monotonic transformation of Z to $h(Z)$.[21]

As second modification to the accumulation function, suppose that the cleansing function is logistic instead of linear. That is, let

$$\mathrm{d}K/\mathrm{d}t = gK(\bar{K} - K) - Z \tag{17}$$

and assume that $\bar{K}^2/4 - \lambda L/g > 0$, so that specialization in M need not lead to the complete destruction of K.[22] The cleansing function is now concave, first increasing in K from $K=0$, reaching a peak, and then decreasing. First note that the autarky pollution function is not affected by the change in the regeneration function (it will be a horizontal line as in Fig. 2). There are, however, now three potential steady state equilibria in autarky: $K=0$, $K=K_{\mathrm{L}}$, and $K=K_{\mathrm{H}}$, where K_{L} occurs on the upward sloping portion of the cleansing function, and K_{H} is on the downward sloping portion. The middle equilibrium, $K=K_{\mathrm{L}}$, is unstable; the other two are stable. Let us consider an autarky economy that has not destroyed its environmental capital and is at the steady state $K=K_{\mathrm{H}}$. Then because the regeneration function is downward sloping in the neighbourhood of K_{H}, the economy will respond to international trade in much the same way as in our previous analysis. The free trade pollution function also looks the same as before (it is a step function as in Fig. 2). For example in the case where free trade prices equal autarky prices, a slight drop in K leads to the development of a comparative advantage in M, and consequently specialization in M; while a slight increase in K leads to specialization in A and pollution falls to zero. Autarky is an unstable free

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[21] The long run production frontier will no longer be strictly convex throughout. However, recall that private costs do not reflect true opportunity costs because of the externality. Long run behavior is represented by the long run supply curve, which continues to be downward sloping in the region where the economy is diversified.

[22] This is analogous to our assumption in footnote 9.

trade equilibrium, and the dynamics of adjustment to free trade follow much the same pattern as in Fig. 2. The analysis of the two country case is also qualitatively similar.

Finally, throughout we have ruled out pollution policy. We have adopted this assumption not because we believe that it is necessarily an accurate description of the real world, but because a serious consideration of policy would detract us from our main focus. If pollution policy was designed to correctly account for the negative long run consequences of Smokestack pollution, and if pollution policy was flexible and could respond to the changing conditions brought about by trade, then free trade could never lead to losses. Alternatively if we assume that pollution policy was a rigid technological standard on emissions (such as a restriction on an allowable λ), then our results carry through as before. As well, once we allow for active pollution policy it is necessary to ask whether such a policy may be used as disguised trade policy. In our two-country model several strategic issues arise, and a full examination of these issues must be left to further work.

8. Conclusion

Free trade may have little or no effect on a polluted small open economy, but it may also have some quite surprising and significant effects as well. When industrial pollutants lower the productivity in environmentally sensitive sectors, trade can play a useful role in spatially separating incompatible industries. And while many environmentalists are concerned that trade allows for the spatial separation of dirty product consumers and dirty product producers, we find that such separation can bring benefits in terms of production efficiency. However, while the separation of incompatible industries brings productivity gains to the world, the division of these gains may not be shared uniformly across countries. Accordingly, we find that the type of separation matters and several surprising results follow: two identical countries can engage in mutually beneficial trade; trade will be mutually beneficial if the demand for the dirty good (Smokestack) is high; one country must lose if the demand for the clean good (Farming) is high; and losses are more likely the less sensitive is Farming to industrial pollutants, and the faster is the environment's cleansing rate. These results seem at first inexplicable, but they are in fact by-products of the terms of trade effects created when the spatial separation of industries creates productivity changes across countries.

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Appendix A

Proof of Proposition 1. Using (14) to replace M in (7), we obtain a simple linear differential equation governing the evolution of the capital stock from any initial value. Solving this initial value problem yields $K(t)=K_0+[K(t=0)-K_0]e^{-gt}$ where K_0 is the steady state capital stock given in Eq. (8). $K'(t)<0$ if $K(t=0)>K_0$, and $K'(t)>0$ if $K(t=0)<K_0$. Therefore the steady state is unique, globally stable, and convergence to the steady state is monotonic.

Proof of Proposition 2. By hypothesis we have $p^*=K_o^{\varepsilon}$, which implies that labour's value of marginal product is equal in both industries and the temporary pattern of production is indeterminate. Suppose this economy produces a level of M slightly greater than M_o. Since M_o was the steady state level, Eq. (1) ensures $dK/dt<0$ at $K=K_o$. K drops below K_o, the economy immediately specializes in M and pollution rises to $Z=\lambda L$. As is apparent from Fig. 2, the economy converges to a stable steady state at K_s. Alternatively, if this economy produces a level of M slightly less than M_o then by parallel reasoning $dK/dt>0$. K rises above K_o, the economy immediately specializes in A and pollution falls to $Z=0$. The economy converges to the stable steady state at $\bar{K}$.

Proof of Proposition 3. Utility must rise if the value of national output rises since pollution has no direct disutility cost. At the outset of trade, $K=K_o$ and world prices may differ from autarky prices. Labourers move into the sector that at free trade prices maximizes (or leaves unchanged) national income. From Proposition 2 we know the dynamics of environmental change either monotonically increase labour productivity in farming if the economy specializes in farming, or leaves unchanged labour productivity in smokestack if the economy specializes in smokestack. As a result, national income cannot fall with trade (and must rise if autarky and free trade prices differ).

Proof of Proposition 4. Autarky is always an unstable trading equilibrium. When $b_m>1/2$ both countries must produce M since world demand is $b_m(wL+w^*L^*)/p_m=b_mL(w+w^*)/p_m$ and this always exceeds one country's maximum supply of L. Note that if $w=p_m$, then $w^*\geq w$; or if $w^*=p_m$, then $w\geq w^*$; in either case we have $b_m(wL+w^*L^*)/p_m>L$ as required. The analysis of Fig. 4 has shown each country moves towards its own stable steady state monotonically. To prove that each country gains recall that during the transition, relative prices adjust continuously to clear markets. Because both countries produce *M*, wages (and hence incomes) must always be equalized across countries. Purchasing power in terms of smokestack output is unaffected by trade ($w/p_M = 1$ before and after trade). Purchasing power in terms of Farm output is $w/p_a = K^{\varepsilon}$, and this must rise monotonically along the adjustment path.

Proof of Proposition 5. Since $b_m < 1/2$, one country must specialize in *A*; we have denoted this country ''Home''. Using an analysis similar to that in the proof of Proposition 2, a locally stable diversified equilibrium will exist in the Foreign country and be reached in the transition to free trade if

$$g(\bar{K} - K^*) = \lambda b_m L[1 + (\bar{K}/K^*)^{\varepsilon}] \equiv \Omega(K^*, \bar{K}) \tag{A1}$$

has at least one positive solution $K^* = \hat{K}^*$ such that (1) $\hat{K}^* > K_s$, the environment's capital stock when all Foreign labor is allocated to Smokestack, and (2) the curve Ω is flatter than the regeneration function $g(\bar{K} - K^*)$ at $K^* = \hat{K}^*$. For b_m sufficiently small (i.e. b_a sufficiently large) we can guarantee at least one positive solution $\hat{K}^* > K_s^*$ because a fall in b_m shifts the entire family of curves $\Omega(K^*, \bar{K})$ in towards the origin. Moreover, we can ensure that condition (2) will hold for sufficiently small b_m because Ω is strictly convex and decreasing in K^*, and because at the initial point K_o^*, we have $\Omega = 2\lambda b_m L > \lambda b_m L = g(\bar{K} - K_o^*)$. Let $\underline{b}$ be the largest b_m such that condition (1) above is satisfied. Then for $b_m < \underline{b}$, the foreign country will approach a locally diversified steady state equilibrium in free trade. To prove the welfare results note that Foreign purchasing power in terms of *M* is unaffected throughout the transition since $w^*/p_m = 1$ before and after trade. However, Foreign's purchasing power in terms of *A* is $w^*/p_a = K^{*\varepsilon}$, which declines monotonically as K^* falls along the transition path. Home's purchasing power in terms of *A* is $w/p_a = K^{\varepsilon}$, which rises with *K* along the transition path. Its wage in terms of *M* is $w/p_m = w/w^* = w/p_a K^{*\varepsilon} = (K/K^*)^{\varepsilon}$. Since *K* rises and K^* falls, Home's purchasing power in terms of *M* must also rise along the transition path.

Proof of Proposition 6. Since $b_m < 1/2$, one country must specialize in *A*; we have denoted this country ''Home''. Referring to the proof of Proposition 5, suppose there exists b_m such that $\underline{b} < b_m < \frac{1}{2}$. Then (A1) does not have a solution in K^* that satisfies condition (1) in Proposition 5. Consequently, $\Omega(K^*, \bar{K}) \geq g(\bar{K} - K^*)$ for all K^* such that $K_s^* \geq K^* > K_o^*$ (as illustrated in Fig. 5(b)). Consequently, using an analysis similar to that in the proof of Proposition 2, the foreign economy will approach a steady state equilibrium in which it is specialized in *M*. The welfare results are proven in the text.

Proof of Proposition 8. The gains from trade and pattern of trade results are simple applications of earlier results. Here we prove the results on the efficiency of the direction of trade. First, we verify the claim that the direction of trade is efficient if $b_m > L^*/(L+L^*)$. Note that if $b_m(L+L^*) > L^* > L$, then both countries must produce Smokestack. World demand for M is then $b_m(\underline{L}+L^*)$. When Foreign specializes in M, world farm output is $A^{*w} = (1-b_m)\{K-(\lambda/g)[b_m(L^*+L)-L^*]\}^{\varepsilon}(L^*+L)$. Now reverse the pattern of specialization by assuming Home specializes in _M, and denote world farm output in this case as A^w. Then $A^w = (1-b_m)\{K-(\lambda/g)[b_m(L^*+L)-L]\}^{\varepsilon}(L^*+L)$. Comparing, we find that $A^{*w} > A^w$ if $L^* > L$, and hence Foreign specializing in farm output is efficient.

Next we show that the direction of trade is inefficient if b_m is sufficiently low. Suppose world demand for M_is L^*_m_units, and this is less than L. If Home specializes in A, we have $\underline{A}^w = K^{\varepsilon}\underline{L} + [\mathrm{K}-(\lambda/g)L^*_m]^{\varepsilon}(L^*-L^*_m)$. If Foreign specializes in A, we have $A^{*w} = K^{\varepsilon}L^* + [\mathrm{K}-(\lambda/g)L^*_m]^{\varepsilon}(L-L^*_m)$. Consequently, $A^{*w} > A^w$ if $L^* > L$.

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