Does Clean or Dirty Matter? Trade, Type of Environmentally Sensitive Industry, and the Environment

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Very preliminary, comments are welcome

Abstract

We analyze the effects of trade on specialization patterns, environmental qualities and welfare gains in a general equilibrium model incorporating endogenous capital accumulation and intertemporal optimization. Both small open economy and two country world are examined. We find that, in the presence of investment, free trade tends to (i) induce specialization, (ii) lower the quality of environment, and (iii) improve the world welfare. This is in contrast to the models abstracting from investment, in which the effects of trade depend crucially on whether the environmental sensitive industry is clean or dirty. On the other hand, as for the welfare effects of trade in each country, the type of environmentally sensitive industry is still relevant.

Keywords: Production externality; Investment; Specialization patterns

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1 Introduction

The purpose of this paper is to highlight the role of investment in the interaction between trade and the environment. We emphasize the negative effects of environmental degradation on production side and focus on three fundamental issues: specialization patterns, environmental qualities, and welfare gains.

How trade and the environment interact with each other? This topic has been extensively discussed in the literature. Many authors formulate environmental degradation as consumer externality.[1] The production externality approach has received relatively less attention.[2] Among those, Taylor and Brander (1997) focus on open-access renewable resources and show that if a country is a resource exporter, then usually it loses from trade in the long run duo to the decline in its resource stock.[3] Copeland and Taylor (1999) focus on incompatible industries and show how pollution can motivate trade by spatially separating these incompatible industries.[4]

In terms of context and result, the above-mentioned two models are quit different, but in terms of model structure, they can be seen as two applications of the same framework corresponding with different sets of parameter values, or specifically, the type of environmentally sensitive industry.[5] In Taylor and Brander (1997), resource intensive industry is environmental sensitive since its productivity increases with the stock of resources.[6] On the other hand, resource intensive industry is dirty in the sense that its production activity decreases the stock of resources. Therefore, Taylor and Brander (1997) have a dirty environmental sensitive industry. In contrast, in Copeland and Taylor (1999), farming is environmental sensitive since its productivity is positively related to the stock of environmental capital. On the other hand, farming is clean in the sense that its production activity emits no pollution. Therefore, Copeland and Taylor (1999) have a clean environmental sensitive industry.

An important contribution of the two models is that they distinguish the short-run effects from the long-run. The quality of the environment is measured by a stock variable (the stock of resources or the stock of

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[1] See, e.g., Markusen (1975a,b), Asako (1979), Copeland and Taylor (1994, 1995) and Ishikawa and Kiyono (2006).

[2] See, e.g., Taylor and Brander (1997), Copeland and Taylor (1999), Benarroch and Thille (2001) and Kotsogiannis and Woodland (2013).

[3] There is a series of work employing the same assumptions in various contexts, including Brander and Taylor (1997, 1998) and Taylor and Brander (1998).

[4] In Copeland and Taylor (1999), pollution arising from one industry reduces the stock of environmental capital and lowers the productivity of the other one.

[5] See Li (2013) for details.

[6] The term "environmentally sensitive industry" sometimes refers to pollution intensive industry identified according to abatement cost or emission intensity. See, e.g., Mohanty and Chaturvedi (2006, p. 7).

environmental capital) evolving over time and the long-run effects thus depend on the dynamic path as well as the steady state. In the long run, however, there is another significant economic activity, investment, which is the central issue in many fields of economic theory but somewhat neglected in the analysis of the interaction between trade and environment.

This paper, therefore, extends the framework of Taylor and Brander (1997) and Copeland and Taylor (1999) to incorporate endogenous capital accumulation and intertemporal optimization. There are several interesting results derived in this paper. First, trade tends to lead to specialization no matter clean or dirty is the environmentally sensitive industry. This differs the models abstracting from investment, where trade leads to specialization only when the environmentally sensitive industry is clean. Second, trade degrades the environment in a small open economy no matter the clean or dirty good it specializes in. In the models abstracting from investment, this happens only when the economy specializes in the dirty good. In a two-country world, the environment become worse in the country completely specialized in the industry not environmentally sensitive. Third, trade increases the world total steady-state consumption and the steady-state equilibrium of complete specialization yields the highest world total consumption.

This paper bridges two strands in the trade literature. One is the dynamic Heckscher-Ohlin model which introduces capital accumulation into the Heckscher-Ohlin framework to examine its implication.[7] The other one is related to the production externality, which has been extensively investigated in trade theory in terms of the validity of well-known trade theorems, trade patterns, welfare gains and other issues.[8]

The structure of the paper is as follows. Section 2 describes the basic model. Section 3 consider the autarky case. Section 4 and 5 investigates the effects of trade in a small open economy and in a two-country world. Section 6 concludes.

2 The Model

There are two primary factors and two tradable intermediate goods. A single nontradable final good is produced from two intermediate goods and can be either consumed or invested. Households choose between consumption and investemnt and maximize their lifetime utility.

Factor of production There are two primary factors: private capital (K) and environmental capital (V). Private capital is freely, costlessly, and

[7] See, e.g., Oniki and Uzawa (1965), Stiglitz (1970), Manning et al. (1993), Baxter (1992); Brecher et al. (2005) and Ono and Shibata (2006).

[8] See, e.g., Herberg and Kemp (1969); Melvin (1969); Panagariya (1980, 1981); Chang (1981); Ishikawa (1994).

instantaneously mobile across industries, thus the rentals are always equalized across active industries. The stock of private capital changes according to

$$\dot{K} = I - \delta K, \tag{1}$$

where I is the investment, δ the depreciation rate.

The stock of environmental capital is given at every point in time, and may evolve over time depending on the flow of pollution (Z), the current level of environmental capital (V), and the natural level of environmental capital ($\bar{V}$): $\dot{V} = E\left(Z, V, \bar{V}\right)$. We follow the formulation of Copeland and Taylor (1999) assuming

$$\dot{V} = g\left(\bar{V} - V\right) - Z, \tag{2}$$

where g is the recovery rate of the environment. The steady-state ($\dot{V} = 0$) level of environmental capital, denoted V_0, is given by $V_0 = \bar{V} - Z/g$. Without regulation, the services of environmental capital is freely used. There is no market for it.

Intermediate good firms There are two intermediate goods: manufacture good (M) and agriculture good (A). Both are tradable and under perfect competition. The representative firm in manufacture industry employs only private capital and emits pollution as a joint product. Assume that one unit of private capital produces one unit of manufacture good and generates $\lambda_m > 0$ units of pollution:

$$M = K_m, \tag{3}$$

$$Z_m = \lambda_m K_m, \tag{4}$$

where M is the output of manufacture good, Z_m the flow of pollution from manufacture. The representative firm in agriculture industry uses both the private capital and the services of environmental capital:

$$A = G\left(V\right) K_a = V^{\varepsilon} K_a, \tag{5}$$

and generates pollution at the emission intensity of $\lambda_a > 0$:

$$Z_a = \lambda_a K_a. \tag{6}$$

$G\left(V\right)$ is the flow of services from the environmental capital stock and, for simplicity, has been assumed to have the very simple form V^{ε} ($0 < \varepsilon \leq 1$).

As we can see, agriculture is environmentally sensitive in the model, and it can be either clean or dirty according to whether $\lambda_a > \lambda_m$ or $\lambda_a < \lambda_m$. We say agriculture is dirty if $\lambda_a > \lambda_m$, and dirty if $\lambda_a < \lambda_m$.

Full employment of private capital requires that, using (3) and (5),

$$K = K_m + K_a = M + \frac{A}{V^{\varepsilon}}. \tag{7}$$

In the short run, the environmental capital stock does not change, thus the productivity of agriculture remains. (7) can be regarded as the expression for the short-run PPF, where M and A is linearly related reflecting the Ricardian structure in the short run.

Given the rental of private capital (r) and the price of manufacture good (p_m), perfect competition and the technology of manufacture (3) require that, if manufacture is active,

$$p_m = r, \tag{8}$$

Agriculture firms maximize profits, treating the environmental capital stock as given. If agriculture is active, it follows the technology (5) that

$$p_a V^{\varepsilon} = r. \tag{9}$$

It is convenient to define P as the relative price of two intermediate goods:

$$P \equiv \frac{p_m}{p_a}. \tag{10}$$

The technologies (3) and (5) also imply that the marginal transformation rate (also the private opportunity cost) of manufacture good in terms of agriculture good satisfies

$$MRT = V^{\varepsilon} \tag{11}$$

If both industries are active, then $P = V^{\varepsilon}$.

It proves to be convenient in the analysis of two-country world if the flow of pollution can be expressed in terms of the output of manufacture good. Substituting (3) into (4) for K_m and (5) into (6) for K_a gives

$$Z = Z_m + Z_a = \lambda_m M + \lambda_a \frac{A}{V^{\varepsilon}}. \tag{12}$$

It follows (7) that $K - M = A/V^{\varepsilon}$. Substituting it into (12) yields

$$Z = \lambda_a K + (\lambda_m - \lambda_a) M. \tag{13}$$

Final good firms There is a single nontradable final good (Q), which is consumed or invested. The final good is produced from two intermediate goods under constant returns to scale and perfect competition. Assume the Cobb-Douglas technology

$$Q = D_m^{b_m} D_a^{b_a}, \tag{14}$$

where $b_m + b_a = 1$, D_m is the input of (also the demand for) manufacture good, D_a the input of (also the demand for) agriculture good.

Final good firms maximize profits, treating the prices of inputs as given. The zero profit condition gives the price (also the cost) of final good (p) in terms of the prices of two intermediate goods

$$p = \frac{p_m^{b_m} p_a^{b_a}}{b}, b \equiv b_m^{b_m} b_a^{b_a}. \tag{15}$$

Households Households choose between consumption (C) and investment (I). The representative household maximizes the lifetime utility $U = \int_0^\infty \ln Ce^{-\rho t}dt$ subject to the budget constraint $rK = p(C+I)$. The optimal problem facing the household can be summarized as follows,

$$\max \int_0^\infty \ln Ce^{-\rho t}dt, \text{ s.t. } rK = p\left(C + \dot{K} + \delta K\right). \tag{16}$$

As a result of dynamic optimization, we obtain the Euler equation $\dot{C}/C = r/p - \delta - \rho, \forall t\,[0,\infty)$ and the transversality condition $\lim_{s\to\infty} \int_0^s \gamma K e^{-\rho t}dt = 0$.[9]

The logarithmic form of the instantaneous utility $\ln C$ implies a simple form of the consumption function along the optimal saddle path

$$C = \rho K, \forall t\,[0,\infty). \tag{17}$$

Therefore, as long as households are optimally saving and investing, K can be seen as a measure of the instantaneous welfare. Substituting (17) into the Euler equation yields

$$\frac{\dot{K}}{K} = \frac{\dot{C}}{C} = \frac{r}{p} - \delta - \rho, \forall t\,[0,\infty). \tag{18}$$

Recall that the environmental capital stock is governed by (2), thus (18) and (2) together determine the paths of K and V. Since ρ, δ, g and $\bar{V}$ are exogenous parameters, the remaining task is to calculate the real rental of private capital r/p and the flow of pollution Z.

3 Autarky

This section analyzes the autarky case serving to be the benchmark. In autarky, all demands for intermediate goods are fulfilled by domestic firms, namely, $D_m = M$, $D_a = A$. Profit maximization of final good firms gives

$$\frac{b_m}{b_a} = \frac{p_m D_m}{p_a D_a}.$$

Substituting (8) and (9) for p_m and p_a yields

$$M = b_m K, A = b_a V^\varepsilon K, \tag{19}$$

and thus the flow of pollution

$$Z = Z_m + Z_a = \lambda K, \lambda \equiv b_m \lambda_m + b_a \lambda_a. \tag{20}$$

[9] γ is the multiplier in Hamiltonian $H = \ln C + \gamma\left(\frac{r}{p}K - C - \delta K\right)$.

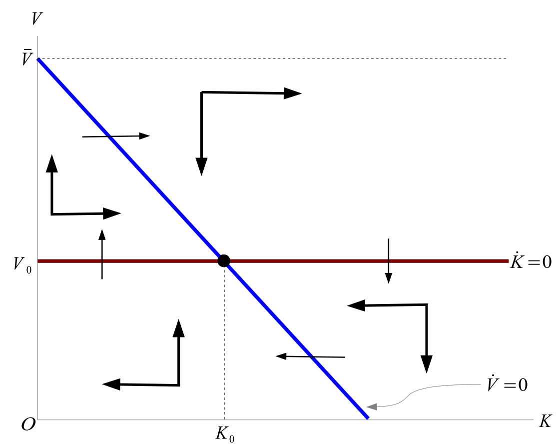


Fig. 1: Dynamics of K and V in autarky

Since both intermediate industries are active, it follows (8), (9) and (15) that at every point in time

$$r/p = bV^{\varepsilon b_a}. \tag{21}$$

Using (21) and (20), the two dynamic equations (18) and (2) become

$$\frac{\dot{K}}{K} = bV^{\varepsilon b_a} - \delta - \rho, \tag{22}$$

$$\dot{V} = g\left(\bar{V} - V\right) - \lambda K, \tag{23}$$

where b and λ are defined by (15) and (20) respectively. Note that now the dynamics of K and V are completely characterized by (22) and (23). Figure 1 gives the phase diagram on the K-V plane. It can be shown that

Proposition 1. *A unique, locally stable steady-state equilibrium* (K_0, V_0) *exists in autarky satisfying*

$$K_0 = \frac{g}{\lambda}\left(\bar{V} - V_0\right), V_0 = \left(\frac{\delta+\rho}{b}\right)^{\frac{1}{\varepsilon b_a}}.$$

Proof. See Appendix A.1 □

In autarky steady state, the stoke of environmental capital depends on the parameters δ, ρ, b_m, b_a and ε, but has nothing to do with the natural level of environmental capital $\bar{V}$. At first glance, this might be somewhat surprising. The intuition comes by realizing the presence of investment. The country with higher level of natural environmental capital will exploit its advantage by investing more. This, in optimal, leads to the convergence of the environmental capital in steady state. Let P_0 denote the autarky steady-state relative price, then $P_0 = V_0^{\varepsilon}$.

It is worthwhile to note that the local stability is quite robust. Suppose the more general evolution function $\dot{V} = E\left(\bar{V}, V, Z\right)$ instead of (2), and $G(V)$ instead of V^{ε} in (5). The local asymptotically stability holds if $\partial E/\partial Z < 0$, $\partial E/\partial V < 0$ and $dG/dV > 0$ at the steady-state point. The global stability, however, is not necessarily true. It is also possible for the existence of a limit cycle where the pair (K, V) repeats the same pattern of evolution.

4 Small Open Economy

In this section we consider a small economy facing the world relative price of intermediate goods $P_w \equiv p_m^w / p_a^w$.

Specialization patterns As shown in (11), the marginal transformation rate between manufacture good and agriculture good is V^{ε} for domestic firms. Due to the Ricardian structure in the short run, specialization patterns of intermediate good industries can be obtained by comparing V^{ε} and P_w. There are three possibilities, (i) $V^{\varepsilon} > P_w$, (ii) $V^{\varepsilon} < P_w$, and (iii) $V^{\varepsilon} = P_w$. When $V^{\varepsilon} > P_w$, the small economy has a comparative advantage in agriculture good and thus completely specializes in agriculture. When $V^{\varepsilon} < P_w$, the small economy has a comparative advantage in manufacture good and thus completely specializes in manufacture. When $V^{\varepsilon} = P_w$, there is no difference for private capital to be allocated in agriculture or manufacture, thus specialization patterns are indeterminate.

Real rental of private capital We move on to the calculation of r/p in each pattern. If $V^{\varepsilon} > P_w$, only agriculture is active, thus $r = p_a^w V^{\varepsilon}$. By (15) we obtain

$$\frac{r}{p} = \frac{p_a^w V^{\varepsilon}}{\frac{(p_m^w)^{b_m}(p_a^w)^{b_a}}{b}} = \frac{bV^{\varepsilon}}{P_w^{b_m}}, \text{ for } V^{\varepsilon} > P_w. \tag{24}$$

If $V^{\varepsilon} < P_w$, only manufacture is active, thus $r = p_m^w$ and

$$\frac{r}{p} = \frac{p_m^w}{\frac{(p_m^w)^{b_m}(p_a^w)^{b_a}}{b}} = bP_w^{b_a}, \text{ for } V^{\varepsilon} < P_w. \tag{25}$$

If $V^{\varepsilon} = P_w$, we have

$$\frac{r}{p} = \frac{bV^{\varepsilon}}{P_w^{b_m}} = bP_w^{b_a}, \text{ for } V^{\varepsilon} = P_w. \tag{26}$$

Note that when the environmental capital stock V is high, the real rental of private capital r/p depends on both V and the world relative price P_w. In contrast, when V is low, r/p depends only on P_w.

Flow of pollution The flow of pollution Z also depends on specialization patterns. If $V^\varepsilon > P_w$, all private capital is employed in agriculture and emits pollution

$$Z = \lambda_a K, \text{ for } V^\varepsilon > P_w. \tag{27}$$

If $V^\varepsilon < P_w$, all private capital is employed in manufacture, thus

$$Z = \lambda_m K, \text{ for } V^\varepsilon < P_w. \tag{28}$$

If $V^\varepsilon = P_w$, since specialization patterns are indeterminate, we just use Z to denote the flow of pollution.

Dynamic system Substituting the expressions of r/p and Z into the two dynamic equations (18) and (2) yields

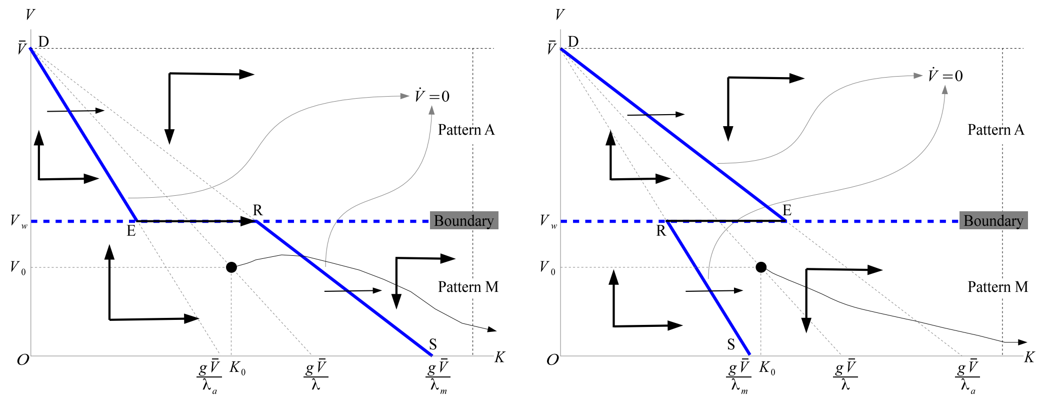
$$\frac{\dot{K}}{K} = \begin{cases} b\left(\frac{V^\varepsilon}{P_w^{b_m}} - P_0^{b_a}\right), & \text{for } V^\varepsilon > P_w, \\ b\left(P_w^{b_a} - P_0^{b_a}\right), & \text{for } V^\varepsilon = P_w, \\ b\left(P_w^{b_a} - P_0^{b_a}\right), & \text{for } V^\varepsilon < P_w. \end{cases} \tag{29}$$

$$\dot{V} = \begin{cases} g\left(\bar{V} - V\right) - \lambda_a K, & \text{for } V^\varepsilon > P_w, \\ g\left(\bar{V} - V\right) - Z, & \text{for } V^\varepsilon = P_w, \\ g\left(\bar{V} - V\right) - \lambda_m K. & \text{for } V^\varepsilon < P_w, \end{cases} \tag{30}$$

where δ and ρ are replaced by P_0. This is a dynamic system with two regimes ($V^\varepsilon > P_w$ and $V^\varepsilon < P_w$) and a boundary in between ($V^\varepsilon = P_w$). Since its properties are crucially depending on the relative magnitude of P_w and P_0, we proceed by examining two cases: (i) $P_w > P_0$ and (ii) $P_w < P_0$. The examination on the knife-edge case $P_w = P_0$ is omitted for the sake of space. Before starting examination, it is convenient to use Pattern A, Pattern M and boundary to denote $V^\varepsilon > P_w$, $V^\varepsilon < P_w$ and $V^\varepsilon = P_w$ respectively.

Higher world relative price Consider the case in which the world relative price P_w is higher than the autarky steady-state relative price P_0: $P_w > P_0$. First, we observe that $\dot{K} > 0$ on the whole K-V plane. This is because, in Pattern A and on the boundary, $P_w^{b_a} - P_0^{b_a} > 0$, and in Pattern M, $V^\varepsilon/P_w^{b_m} - P_0^{b_a} > P_w^{b_a} - P_0^{b_a} > 0$ for $V^\varepsilon > P_w$. Therefore, private capital, as well as consumption, keeps growing over time.

The phase diagrams are helpful for grasping a concrete image of the dynamics. Figure 2a corresponds with the case of dirty agriculture ($\lambda_a > \lambda_m$), and Figure 2b with the case of clean agriculture ($\lambda_a < \lambda_m$). The line segments DE and RS give the points satisfying $\dot{V} = 0$. It is clear that there is no steady-state equilibrium point in both case. The small economy specializes in manufacture good and keeps investing in private capital. Starting from the autarky equilibrium point, (K_0, V_0) in the



(a) Agriculture is dirty ($\lambda_a > \lambda_m$)

(b) Agriculture is clean ($\lambda_a < \lambda_m$)

Fig. 2: Dynamics of K and V in a small open economy when $P_w > P_0$

figure, if agriculture is dirty, there is an environmental enhancement in the short run, but in the long run the environment degrades. The reason is, when trade is opened, the flow of pollution is reduced initially since manufacture has lower pollution intensity. This enhances the environment in the short run. In the long run, however, the flow of pollution increases with the accumulation of private capital and, soon or later, the environment becomes worse than autarky. In contrast, if agriculture is clean, then the environment degrades initially and keeps degrading over time. The results can be summarized in the following proposition, where SP, WE and EI represent the results about specialization patterns, welfare gains and environmental impacts.

Proposition 2. *If the world relative price is higher than autarky $P_w > P_0$, then a small economy opened to the world*

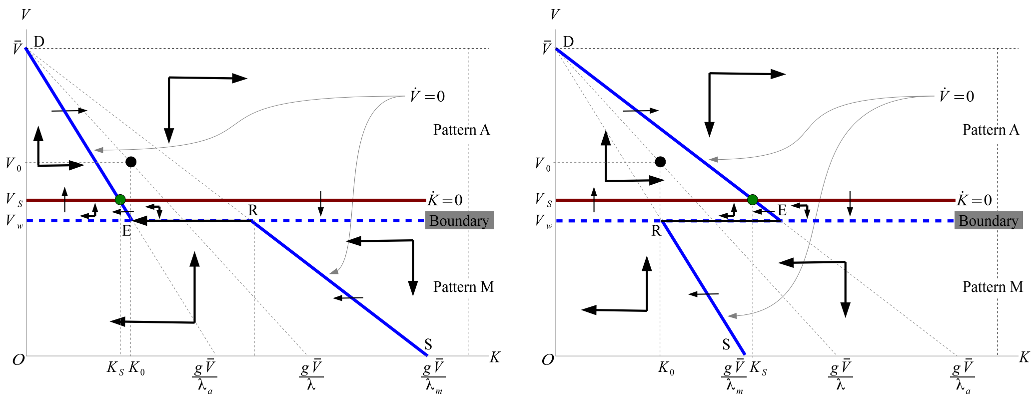
(i. SP) specializes in manufacture.

(ii. WE) The free trade consumption grows over time. The growth rate converges to $b\left(P_w^{b_a} - P_0^{b_a}\right)$.

(iii. EI) Starting from the autarky steady-state equilibrium, in the short run, free trade enhances (degrades) the environment if agriculture is dirty (clean). In the long run, trade will drive the environmental capital stock to zero.

Lower world relative price What happens if the world relative price is lower than autarky? Given $P_w < P_0$, we have $\dot{K} < 0$ in Pattern M and on the boundary. In Pattern A, the sign of $\dot{K}$ depends on the sign of $V^\varepsilon / P_w^{b_m} - P_0^{b_a}$. Simple calculation gives

$$V_S = \left(P_w^{b_m} P_0^{b_a}\right)^{1/\varepsilon} = V_w^{b_m} V_0^{b_a} \in (V_w, V_0),$$



(a) Agriculture is dirty ($\lambda_a > \lambda_m$)

(b) Agriculture is clean ($\lambda_a < \lambda_m$)

Fig. 3: Dynamics of K and V in a small open economy when $P_w < P_0$

so that $\dot{K} = 0$ when $V = V_S$, and $\dot{K} \gtrless 0$ when $V \gtrless V_S$. Using V_S, Pattern A can be further divided into two regions. Figure 3a illustrates the dynamics corresponding with the case of dirty agriculture, while Figure 3b with the case of clean agriculture. The steady-state equilibrium point (K_S, V_S) lies within Pattern A. The results are summarized as follows.

Proposition 3. *If the world relative price is lower than autarky $P_w < P_0$, a small economy opened to the world*

(i. SP) has a locally stable, unique steady-state equilibrium (K_S, V_S) so that the small economy completely specializes in agriculture, where

$$K_S = \frac{g}{\lambda_a}\left(\bar{V} - V_S\right), V_S = \left(\frac{\delta+\rho}{b} P_w^{b_m}\right)^{\frac{1}{\varepsilon}}.$$

(ii. WE) Starting from the autarky steady-state equilibrium, in the short run, the free trade consumption grows. In the long run, if agriculture is dirty, the free trade steady-state consumption can be higher or lower than autarky; if agriculture is clean, then the free trade steady-state is necessarily higher than autarky.

(iii, EI) Starting from the autarky equilibrium, in the short run, free trade degrades (enhances) the environment if agriculture is dirty (clean). In the long run, trade will degrade the environment.

Table 1 summarizes the effects of trade in a small open economy for both $P_w > P_0$ and $P_w < P_0$. It is striking that trade always leads to environmental degradation in the long run, even it completely specializes in clean good (see Figure 3b). The intuition is, however, quit straightforward. When trade opens, the small economy specializes in clean good

		Dirty agriculture			Clean agriculture		
		SP	WE	EI	SP	WE	EI
$P_w > P_0$	Short-run	M	$+$	$+$	M	$+$	$-$
	Steady-state	M	$+$	$-$	M	$+$	$-$
$P_w < P_0$	Short-run	A	$+$	$-$	A	$+$	$+$
	Steady-state	A	?	$-$	A	$+$	$-$

Tab. 1: The effects of trade in a small economy

and the environment is enhanced in the short run. On the other hand, the stock of private capital has been increasing through investment so that more and more pollution is generated. In steady state, the latter effects dominate the former.

5 Two-country world

In this section we consider a world with two countries, Home and Foreign. To neutralize other factors for trade, we assume two identical countries. Unlike in a small open economy, the world relative price P_w endogenously depends on the stock of environmental capital of two countries (V and V^*), the size of two countries (K and K^*), as well as the share of intermediate goods in final good (b_m). These, except for b_m, are again endogenously determined.

To tackle this problem, the relative magnitude of environmental capital stock is crucial for it determines the comparative advantage and thus the possible specialization patterns. If $V > V^*$, then Home has a comparative advantage on agriculture good, thus Home always produces agriculture good while Foreign always produces manufacture good. Moreover, there are three possible specialization patterns: (i) Home produces both while Foreign completely specializes; (ii) Both Home and Foreign completely specialize; (iii) Home completely specializes while Foreign produces both. For convenience, we use Pattern I, Pattern II and Pattern III to refer to the possible patterns (i), (ii) and (iii) respectively.

If $V = V^*$, both countries remain diversified.[10] This is referred as Pattern IV. Finally, if $V < V^*$, the possible specialization patterns can be obtained by swapping "Home" and "Foreign" in the case $V > V^*$. This is because there are always two symmetric equilibria of each type for the two identical countries. Let Pattern I', II', III' denote the symmetric patterns. Table 2 summarizes the possible patterns, where, for example, "I (D, M^*)" means that in Pattern I Home produces both and Foreign produces only manufacture good.

[10] As an extreme case, it is possible for a country happens to produce only one good.

	$V>V^*$	$V=V^*$		$V<V^*$
I	(D,M^*)		I'	(M,D^*)
II	(A,M^*)	IV (D,D^*)	II'	(M,A^*)
III	(A,D^*)		III'	(D,A^*)

Tab. 2: Possible specialization patterns

In the following we investigate the properties of each pattern, including the existence of steady state, the stability, and the effects of trade on the environment and welfare. As mentioned above, it is sufficient to just focus on the analysis of $V>V^*$ and $V=V^*$.

Pattern I In Pattern I, Home remains diversified but Foreign completely specializes. We want to know how the world relative price (P_w), the real rentals of private capital (r/p and r^*/p^*), and the flows of pollution (Z and Z^*) are determined in this pattern.

Since Home produces both intermediate goods, the world relative price is determined by the environmental capital stock in Home: $P_w = V^{\varepsilon}$. Since both countries produce manufacture good, the rentals of private capital are equalized across countries $r=r^*=p_m^w$; using (25), we have the real rentals equalized across countries, too.

$$\frac{r}{p}=\frac{r^*}{p^*}=bP_w^{b_a}=bV^{\varepsilon b_a}. \tag{31}$$

The world demand for manufacture good, denoted D_m^w, is given by

$$D_m^w=b_m\frac{rK+r^*K^*}{p_m^w}=b_m\left(K+K^*\right). \tag{32}$$

Foreign supplies $M^*=K^*$ units of manufacture good, thus the world market clearing condition requires

$$M=D_m^w-K^*=b_mK-b_aK^*. \tag{33}$$

Since $M>0$ in this pattern, there is a constraint on the relative country size

$$\frac{K}{K^*}>\frac{b_a}{b_m}, \tag{34}$$

If (34) does not hold, there is no positive solution of M and then the two countries cannot lie in Pattern I. Given M and M^*, the flows of pollution in both countries are, using (13),$Z=\lambda_aK+\left(\lambda_m-\lambda_a\right)M$

$$Z=\lambda K-b_a\left(\lambda_m-\lambda_a\right)K^*, \tag{35}$$

$$Z^*=\lambda_mK^*. \tag{36}$$

Substituting (31), (35) and (36) into (18) and (2), as well as its Foreign counterpart, yields the two-country dynamic system in Pattern I:

$$\begin{aligned}\frac{\dot{K}}{K} &= bV^{\varepsilon b_a} - \delta - \rho, \\ \dot{V} &= g\left(\bar{V} - V\right) - \lambda K + b_a\left(\lambda_m - \lambda_a\right)K^*, \\ \frac{\dot{K}^*}{K^*} &= bV^{\varepsilon b_a} - \delta - \rho, \\ \dot{V}^* &= g\left(\bar{V} - V^*\right) - \lambda_m K^*.\end{aligned}$$

Simple calculation gives the steady-state environmental capital stock in Home

$$V_T = V_0 = \left(\frac{\delta + \rho}{b}\right)^{\frac{1}{\varepsilon b_a}},$$

and a linear relationship between the steady-state private capital stock in Home K_T and in Foreign K_T^*

$$K_T = \frac{b_a\left(\lambda_m - \lambda_a\right)}{\lambda}K_T^* + \frac{g}{\lambda}\left(\bar{V} - V_T\right) = \frac{b_a\left(\lambda_m - \lambda_a\right)}{\lambda}K_T^* + K_0, \tag{37}$$

where K_0 and V_0 is the autarky steady-state stocks of private capital and environmental capital. The steady-state environmental capital stock in Foreign is also linearly related to K_T^*

$$V_T^* = \bar{V} - \frac{\lambda_m}{g}K_T^*. \tag{38}$$

Therefore, the steady-state equilibrium vector $\{V_T, K_T, K_T^*, V_T^*\}$ has one dimension of freedom.

Note that the condition $V > V^*$ in Pattern I implies another constraint on the relative country size:[11]

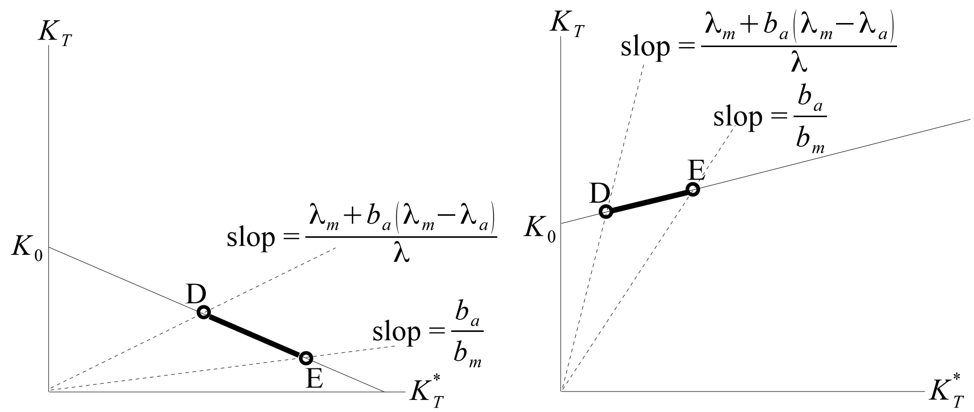
$$\frac{K_T}{K_T^*} < \frac{\lambda_m + b_a\left(\lambda_m - \lambda_a\right)}{\lambda}. \tag{39}$$

Compared with (34), the existence of a nonempty set of steady-state equilibria requires that $b_a/b_m < \left[\lambda_m + b_a\left(\lambda_m - \lambda_a\right)\right]/\lambda$, which can be simplified into

$$b_m\lambda_m > b_a\lambda_a. \tag{40}$$

Figure 4 illustrates the linear relationship between K_T and K_T^*. Any point on the line segment DE, determined by (37) and constraints (34) and (39), is a steady-state equilibrium in Pattern I (except for two end points D and E). According to (38), larger K_T^* means smaller V_T^*, thus

[11] Since $V > V^*$, we must have $V_T > V_T^*$. Substituting V_T and V_T^* into $\dot{V} = \dot{V}^* = 0$ for V and V^*, and using $V_T > V_T^*$ we can obtain $-\lambda K + b_a\left(\lambda_m - \lambda_a\right)K^* > -\lambda_m K^*$ in steady state. This directly gives (39).



(a) Agriculture is dirty ($\lambda_a > \lambda_m$) (b) Agriculture is clean ($\lambda_a < \lambda_m$)

Fig. 4: Steady-state private capital stocks in Pattern I in a two-country world

V_T^* declines moving along DE towards E. Moreover, if agriculture is dirty (Figure 4a), the slope of DE are negative. This implies that if there is a country getting better off (higher private capital stock and thus consumption), the other one must be worse off. On the contrary, if agriculture is clean (Figure 4b), DE is positively slopped.[12] An increase in private capital stock in one country is a win-win adjustment. The following proposition summarized the results.

Proposition 4. *Given that $b_m\lambda_m > b_a\lambda_a$ holds, in a free trade two-country world,*

(i. Steady-state; SP) There is a set of steady-state equilibria satisfying $V > V^*$, in which Home remains diversified and Foreign specializes in manufacture. Every steady-state equilibrium $\{V_T, K_T, K_T^*, V_T^*\}$ satisfies (38), (37), (38), (34) and (39). Moreover, every steady-state equilibrium is stable if and only if $\lambda + b_a(\lambda_a - \lambda_m) > 0$. But no steady-state equilibrium is asymptotically stable.

(ii. Steady-state; WE) In Home, if agriculture is dirty (clean), then the free trade steady-state consumption is necessarily lower (higher) than autarky. In Foreign, if agriculture is dirty, then the free trade steady-state consumption is necessarily higher than autarky. The free trade world total steady-state consumption is necessarily higher than autarky.

(iii. Steady-state; EI) In steady state, the environment remains the

[12] It is easy to show that $b_a(\lambda_m - \lambda_a)/\lambda < b_a/b_m$ always holds, thus DE must intersect the two lines starting from the origin with the slops b_a/b_m and $(\lambda_m + b_a(\lambda_m - \lambda_a))/\lambda$. Also, according to the non-empty condition (40), we can obtain that, if $\lambda_a > \lambda_m$ then $1 > (\lambda_m + b_a(\lambda_m - \lambda_a))/\lambda > b_a/b_m$, and if $\lambda_a < \lambda_m$ then $(\lambda_m + b_a(\lambda_m - \lambda_a))/\lambda > b_a/b_m > 1$.

same as autarky in Home, while degrades in Foreign.

Proof. See Appendix A.2. □

Pattern II Consider the case in which both countries remain completely specialized. The rentals in Home and Foreign are

$$r = p_a^w V^\varepsilon, r^* = p_m^w.$$

The world supply of manufacture good is provided only by Foreign

$$M^* = K^*.$$

On the other hand, the world demand is

$$D_m^w = \frac{b_m\left(rK + r^*K^*\right)}{p_m^w} = b_m\left(\frac{V^\varepsilon}{P_w}K + K^*\right).$$

The world market clearing condition will determine the world relative price as follows:

$$P_w = \frac{b_m K}{b_a K^*} V^\varepsilon. \tag{41}$$

Note that in Pattern II, we have $V^{*\varepsilon} \leq P_w \leq V^\varepsilon$. This imposes a constraint on the relative size of countries:

$$\frac{b_a}{b_m}\left(\frac{V^*}{V}\right)^\varepsilon \leq \frac{K}{K^*} \leq \frac{b_a}{b_m} \tag{42}$$

Using (41) and (24) yields the real rental of private capital in Home

$$\frac{r}{p} = b_a \left(\frac{K^*}{K}\right)^{b_m} V^{\varepsilon b_a}. \tag{43}$$

Using (41) and (25) yields the real rental in Foreign

$$\frac{r^*}{p^*} = b_m \left(\frac{K}{K^*}\right)^{b_a} V^{\varepsilon b_a}. \tag{44}$$

The flows of pollution are simple

$$Z = \lambda_a K, Z^* = \lambda_m K^*. \tag{45}$$

Substituting (43), (44) and (45) into (18) and (2) for r/p and Z, and doing the same for Foreign, we can obtain the dynamic system in Pattern II

$$\begin{aligned}
\frac{\dot{K}}{K} &= b_a \left(\frac{K^*}{K}\right)^{b_m} V^{\varepsilon b_a} - \delta - \rho, \\
\dot{V} &= g\left(\bar{V} - V\right) - \lambda_a K, \\
\frac{\dot{K}^*}{K^*} &= b_m \left(\frac{K}{K^*}\right)^{b_a} V^{\varepsilon b_a} - \delta - \rho, \\
\dot{V}^* &= g\left(\bar{V} - V^*\right) - \lambda_m K^*.
\end{aligned}$$

In steady state, the stock of private capital must satisfy

$$\frac{K_T}{K_T^*} = \frac{b_a}{b_m}. \tag{46}$$

Substituting into the dynamic system yields the steady-state environmental capital stock in Home

$$V_T = V_0 = \left(\frac{\delta + \rho}{b}\right)^{\frac{1}{\varepsilon b_a}},$$

which is the same as in Pattern I, as well as autarky. The stead-state private capital stock in Home is then

$$K_T = \frac{g\left(\bar{V} - V_T\right)}{\lambda_a}, \tag{47}$$

while in Foreign

$$K_T^* = \frac{b_m g\left(\bar{V} - V_T\right)}{b_a \lambda_a}, V_T^* = \bar{V} - \frac{b_m \lambda_m}{b_a \lambda_a}\left(\bar{V} - V_T\right). \tag{48}$$

Since in Pattern II, it is required that $V_T > V_T^*$, which also leads to condition (40). The results are summarized as follows.

Proposition 5. *Given that $b_m \lambda_m > b_a \lambda_a$ holds, in a free trade two-country world,*

(i. Long-run; SP) there is an unique, locally half-stable (stable on one side of the equilibrium: $K/K^* \leq b_a/b_m$) steady-state equilibrium so that both countries completely specialize. The steady-state equilibrium $\{V_T, K_T, K_T^*, V_T^*\}$ is described by (38), (47), and (48).

(ii. Long-run; WE) In Home, if agriculture is dirty (clean), then free trade steady-state consumption is necessarily lower (higher) than autarky. In Foreign, if agriculture is dirty, then the free trade steady-state private capital is necessarily higher than autarky.

(iii. Long-run; EI) In steady state, the environment in Home remains the same as autarky, while degrades in Foreign.

Proof. See Appendix A.3. □

Pattern III In this pattern, Foreign produce both intermediate goods, thus the world relative price are determined by Foreign environment: $P_w = V^{*\varepsilon}$. The real rental in Home is, using (24),

$$\frac{r}{p} = \frac{bV^{\varepsilon}}{P_w^{b_m}} = bV^{*\varepsilon b_a}\left(\frac{V}{V^*}\right)^{\varepsilon}, \tag{49}$$

and that in Foreign is, using (26),

$$\frac{r^*}{p^*} = bP_w^{b_a} = bV^{*\varepsilon b_a}. \tag{50}$$

We have two observations for Pattern III. First, as the constraint (34) for Pattern I and (42) for Pattern II, the constraint for Pattern III is

$$\frac{K}{K^*} < \frac{b_a}{b_m} \left(\frac{V^*}{V} \right)^{\varepsilon}. \tag{51}$$

Second, we have $r/p > r^*/p^*$ for $V > V^*$. Hence the growth rate of private capital in Home is higher than Foreign, and the ratio K/K^* increases over time. Soon or later, (51) will break down and this two-country world leaves Pattern III. This argument is summarized in the following proposition.

Proposition 6. *There is no steady state in Pattern III..*

Pattern IV Now consider the case of $V = V^*$. Note that autarky equilibrium is also a free trade equilibrium, which is one of the equilibria in Pattern IV. The dynamic system has a relatively simple form in Pattern IV,

$$\begin{aligned} \frac{\dot{K}}{K} &= bV^{\varepsilon b_a} - \delta - \rho, \\ \dot{V} &= g\left(\bar{V} - V\right) - Z, \\ \frac{\dot{K}^*}{K^*} &= bV^{*\varepsilon b_a} - \delta - \rho, \\ \dot{V}^* &= g\left(\bar{V} - V^*\right) - Z^*. \end{aligned}$$

The world market clearing condition for manufacture good is

$$M + M^* = b_m \left(K + K^*\right). \tag{52}$$

Together with (13) and $V = V^*$, we obtain the same level of steady-state environmental capital stocks as autarky

$$V_T = V_T^* = V_0 = \left(\frac{\delta + \rho}{b} \right)^{\frac{1}{\varepsilon b_a}}.$$

The world total steady-state private capital stock is the same as autarky, but may not be allocated uniformly across countries:

$$K_T + K_T^* = 2K_0. \tag{53}$$

Since specialization patterns are indeterminate when $V = V^*$, we cannot express M in terms of (K, V, K^*, V^*) in (13). The check of stability is unavailable if there is no further assumption on the behavior of firm. Without the support of stability, $V = V^*$ is no more than a knife-edge situation, and for most of time we may safely ignore it.

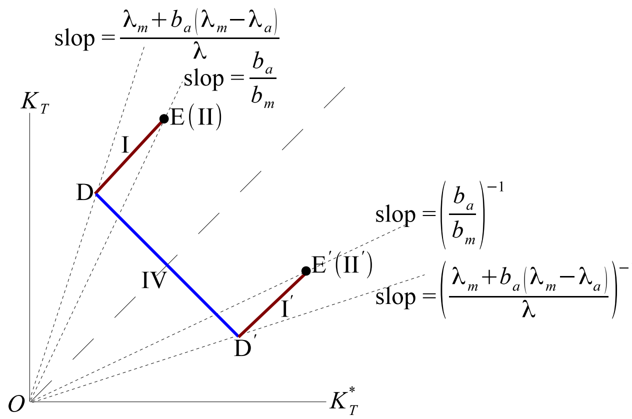


Fig. 5: The relationship between specialization patterns ($\lambda_m > \lambda_a$)

The relationship between patterns We have analyzed four patterns (I, II, III and IV) and their properties one by one. Table 3 in Appendix A.4 serves to be a quick index for our results. With these results in hand, we now are able to examine how these patterns are related to each other.

First, we notice that the unique steady-state equilibrium in Pattern II can be arrived by letting K_T/K_T^* in Pattern I approaches b_a/b_m. This can be verified by letting $K_T/K_T^* = b_a/b_m$ in (33) to obtain $M = 0$. Therefore, point E in Figure 4b is actually the unique equilibrium in Pattern II.

Second, if we let K_T/K_T^*in Pattern I goes in another direction to $[\lambda_m + b_a(\lambda_m - \lambda_a)]/\lambda$, we arrive at an equilibrium in Pattern IV. To see this, substituting $K_T/K_T^* = [\lambda_m + b_a(\lambda_m - \lambda_a)]/\lambda$ into the dynamic system in Pattern I and letting $\dot{K} = \dot{K}^* = \dot{V} = \dot{V}^* = 0$, we obtain $V_T^* = V_T = V_0$ and $K_T + K_T^* = 2K_0$.

Third, in the K^*-K plane, the equilibria in Pattern IV lies on a straight line with slop -1 according to (53). The equilibria in Pattern I lie on a line segment with slop $b_a(\lambda_m - \lambda_a)/\lambda$. It is easy to check that $b_a(\lambda_m - \lambda_a)/\lambda > -1$.

These observations are illustrated in Figure 5, where we assume agriculture is clean ($\lambda_m > \lambda_a$). In the figure, the line segment DE (except for end points D and E) contains the steady-state equilibria in Pattern I, point E is the steady-state equilibrium in Pattern II, the line segment DD' contains the steady-state equilibria in Pattern IV. While D'E' represents Pattern I' and Pattern II' of the symmetric counterpart ($V < V^*$).

Notice that the world total steady-state consumption is determined by $C_T + C_T^* = \rho(K_T + K_T^*)$. It is apparent from Figure 5 that point E, as well as E', achieves the highest $K_T + K_T^*$ thus is the most efficient world equilibrium. The above arguments can be summarized as follows.

Proposition 7. *The locally half-stable complete specialization equilibrium, if exists, is the most efficient world equilibrium in terms of the world total steady-state consumption.*

Recall the results associated with Pattern I and Pattern II. First, the two patterns share a same feature that Foreign completely specializes in manufacture good. Second, the equilibrium in Pattern I and Pattern II are stable (though not asymptotically stable in Pattern I), thus we can make the following statement:

Remark 8. In a free trade two-country world, there is an tendency for a country to completely specialize in manufacture, while the other country may either completely specialize in agriculture or remain diversified.

6 Conclusion

In a world without investment, the environmentally sensitive industry being clean or dirty matters a lot since it determines the shape of the steady-state PPF, which in turn determines specialization patterns and other effects of trade. However, in a world where investment is available, being clean or dirty does not matter in terms of specialization patterns. As shown in our model, in both a small open economy and a two-country world, there exists a strong tendency towards specialization. The intuition here bears some resemblance with the dynamic Heckscher-Ohlin model. That is, when private capital can be produced and invested, it is actually, from the long-run perspective, a intermediate good rather than a primary factor of production. As first shown in Samuelson (1951), if there is only one primary factor and if there is no externality, the PPF must be linear (or contain a hyperplane). What is new in this paper is that, recalling the only primary factor (environmental capital) is subject to production externalities, the existence of production externality renders the PPF even more convex as long as production technology differs across industries.

In the case of two-country world, we assume that both countries are identical. It would be interesting to consider a country with dirty agriculture while the other with clean agriculture. Moreover, since the technology is confined to Leontief type in our model, there is no space for abatement. It would be also interesting to consider the substitution between pollution and capital, and environmental policies.

A Appendix

A.1 Proof of Proposition 1

The uniqueness is obvious from (22) and (23). The Jacobian around the steady-state point is

$$J \equiv \frac{\partial\left(\dot{K},\dot{V}\right)}{\partial\left(K,V\right)} = \begin{bmatrix} 0 & b\varepsilon b_a V^{\varepsilon b_a - 1} \\ -\lambda & -g \end{bmatrix}.$$

The local stability directly follows $\det J = \lambda b\varepsilon b_a V^{\varepsilon b_a - 1} > 0$ and tr$J = -g < 0$.

A.2 Proof of Proposition 4

Proof of (i) Since other results can be easily obtained in the analysis prior to the proposition, we only prove the stability. The Jacobian around the steady-state points is

$$J \equiv \frac{\partial\left(\dot{K},\dot{V},\dot{K}^*,\dot{V}^*\right)}{\partial\left(K,V,K^*,V^*\right)} = \begin{bmatrix} 0 & b\varepsilon b_a V^{\varepsilon b_a - 1} & 0 & 0 \\ -\lambda & -g & -b_a\left(\lambda_a - \lambda_m\right) & 0 \\ 0 & b\varepsilon b_a V^{\varepsilon b_a - 1} & 0 & 0 \\ 0 & 0 & -\lambda_m & -g \end{bmatrix}.$$

Routine calculation gives the characteristic equation

$$|J - \sigma I| = \sigma^4 + 2g\sigma^3 + \left(B + g^2\right)\sigma^2 + Bg\sigma = 0,$$

where $B \equiv b\varepsilon b_a V^{\varepsilon b_a - 1}\left[\lambda + b_a\left(\lambda_a - \lambda_m\right)\right]$. Factorization gives

$$|J - \sigma I| = \sigma\left(\sigma + g\right)\left(\sigma^2 + g\sigma + B\right).$$

If $B > 0$, which implies $\lambda + b_a\left(\lambda_a - \lambda_m\right) > 0$, we have $\sigma_1 = 0$, $\sigma_2 = -g < 0$, $\sigma_3, \sigma_4 < 0$. This proofs the stability. Since $\sigma_1 = 0$, it is not asymptotically stable. If $B < 0$, then one eigenvalue is greater than zero. This gives the instability.

Proof of (ii) By (37) and noting that $K_T^* > 0$, we have $K_T \lesseqgtr K_0$ if $\lambda_a \gtreqless \lambda_m$. By the consumption function (17), the free trade steady-state consumption in Home C_T satisfies that $C_T \lesseqgtr C_0$ if $\lambda_a \gtreqless \lambda_m$. Similarly, according to (38) and $V_T^* < V_T = V_0$, $K_T^* > K_0$ and thus $C_T^* > C_0$.

As for the world total steady-state consumption $C_T + C_T^* = \rho\left(K_T + K_T^*\right)$. By (37), $K_T + K_T^* = \lambda_m K_T^*/\lambda + K_0$. Substituting (38) for K_T^* yields $K_T + K_T^* = K_0 + g\left(\bar{V} - V_T^*\right)/\lambda$. Given that $V_T^* < V_T = V_0$ in Pattern I, $g\left(\bar{V} - V_T^*\right)/\lambda > K_0$ and thus $K_T + K_T^* > 2K_0$.

Proof of (iii) This can be directly obtained from the expression of V_T and the condition $V_T > V_T^*$.

A.3 Proof of Proposition 5

Since other results can be easily obtained in the analysis prior to the proposition, we only prove the stability. The Jacobian around the steady-state point is

$$J = \begin{bmatrix} -b_a b_m \left(\frac{K^*}{K}\right)^{b_m} V^{\varepsilon b_a} & b_a \left(\frac{K^*}{K}\right)^{b_m} \varepsilon b_a V^{\varepsilon b_a - 1} & b_a b_m \left(\frac{K}{K^*}\right)^{b_a} V^{\varepsilon b_a} & 0 \\ -\lambda & -g & 0 & 0 \\ b_a b_m \left(\frac{K^*}{K}\right)^{b_m} V^{\varepsilon b_a} & b_m \left(\frac{K}{K^*}\right)^{b_a} \varepsilon b_a V^{\varepsilon b_a - 1} & -b_a b_m \left(\frac{K}{K^*}\right)^{b_a} V^{\varepsilon b_a} & 0 \\ 0 & 0 & -\lambda_m & -g \end{bmatrix}.$$

Simple calculation gives

$$\begin{aligned} |J_1| &= -B < 0, \\ |J_2| &= Bg + D\lambda_a > 0, \\ |J_3| &= -2\lambda_a \frac{b_a}{b_m} BD < 0, \\ |J| &= -g\,|J_3| > 0, \end{aligned}$$

where $B \equiv b_a b_m \left(\frac{K^*}{K}\right)^{b_m} V^{\varepsilon b_a} > 0$, $D \equiv b_a \left(\frac{K^*}{K}\right)^{b_m} \varepsilon b_a V^{\varepsilon b_a - 1} > 0$. Hence J is negative definite, which proves the asymptotical stability. Note that this holds around only one side of the equilibrium point, namely $K/K^* \le b_a/b_m$. On the other side, namely $K/K^* > b_a/b_m$, the condition required for Pattern II fails.

A.4 Summary of two-country world

Pattern I		
	A Dirty	A Clean
SP	(D, M^*)	(D, M^*)
WE	$(-, +)$	$(+, ?)$
EI	$(0, -)$	$(0, -)$
World Welfare	$+$	$+$

(a) Pattern I

Pattern II		
	A Dirty	A Clean
SP	(A, M^*)	(A, M^*)
WE	$(-, +)$	$(+, ?)$
EI	$(0, -)$	$(0, -)$
World Welfare	$+$ (maximum)	$+$ (maximum)

(b) Pattern II

Pattern IV		
	A Dirty	A Clean
SP	(D, D^*)	(D, D^*)
WE	indeterminate	indeterminate
EI	$(0, 0)$	$(0, 0)$
World Welfare	0	0

(c) Pattern IV

Tab. 3: Steady-state effects of trade in two-country world

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