Pollution Policy and Liberalization of Trade in Environmental Goods*

Alain-Désiré Nimubona†

Abstract

During the Doha Round at the World Trade Organization (WTO), reductions in trade barriers on environmental goods (EG) were put forward as a means of helping developed and developing countries alike deal with current environmental problems. We examine the potential effectiveness of such a strategy in countries that rely on imports for their needs in EG. We point out that liberalizing trade in EG might in fact lead to less stringent environmental regulations, resulting in an actual rise in pollution levels. We then show conditions under which the environmental effectiveness and the welfare improvement objective of this trade reform are compromised.

Keywords: eco-industry, environmental regulation, trade liberalization

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†Department of Economics - University of Waterloo, and CIRANO, animubon@uwaterloo.ca.

1. Introduction

In recent years, a number of regional and international initiatives have been introduced to liberalize trade in environmental goods (EG) such as scrubbers, mufflers, catalytic converters, and dust collectors. During the late 1990's, for example, the Asia-Pacific Economic Cooperation economies aimed at achieving zero-tariffs on EG by 2005 or before. Similarly, the 2001 US-Jordan Free Trade Agreement sought to eliminate tariffs on many EG over a ten-year period. The 2002 Canada-Costa Rica Free Trade Agreement, in turn, provided immediate duty-free access to most EG (Kennett and Steenblik 2005). At its fourth Ministerial meeting held in Doha (Qatar) in 2001, the World Trade Organization (WTO) also recognized the importance of liberalizing trade in EG (see Paragraph 31(iii) of the Doha Ministerial Declaration).[1]

A key objective of such liberalization initiatives is to enhance environmental protection in both developed and developing countries while promoting their economic development. Countries that import EG, the assumption goes, will increase their demand for EG as a response to reduced prices stemming from import tariff cuts. The resulting decrease in compliance costs will in turn induce local regulators to set more ambitious environmental targets. However, because of the imperfectly competitive environment in which EG

[1] In fact, these trade agreements also targeted environmental services, which include wastewater and solid waste management services. However, environmental goods and services are subject to different trade regimes. At the WTO, for example, negotiations on the liberalization of trade in environmental goods and services are held in two distinct bodies: the Negotiating Group on Non-Agricultural Market Access and the Special Session of the Council for Trade in Services. As this paper focuses on trade liberalization in environmental goods, it therefore leaves aside specific issues related to environmental services.

are produced, these environmental benefits of trade liberalization in EG are not always realized. Indeed, although the large number of firms that operate in the different segments of the eco-industry suggests a competitive environment, the following facts reveal a rather different picture. First, only a few multinational firms dominate the environmental market. Moreover, while it may be optimal for these multinationals to compete among themselves, it may sometimes be rational for them to cooperate through contracting and subcontracting. Second, a large number of small firms specialize in the provision of a narrow range of goods and services in particular geographic areas or market niches (OECD 2001). Finally, the relative dominance of different segments of the eco-industry varies across countries according to the evolution of their environmental regulations. As a consequence, the top 20 exporters of environmental goods in 2002 accounted for about 93 per cent of world exports. This degree of concentration is greater than in overall merchandise trade where the top 20 exporters accounted for just a little over 82 per cent of world exports (Bora and Teh 2004).

Within this imperfectly competitive environment, different actors in the trade and environmental regulatory processes may interact strategically. On the one hand, EG-import tariffs may help EG-importing countries to extract rents from foreign eco-industrial firms. On the other hand, if EG import tariffs are eliminated or reduced, countries that do not produce EG may use environmental policies as a substitute for EG-import tariffs. It is worth mentioning that tariff barriers to trade in EG are significantly lower in most developed countries, and for most EG, than in the rest of the world. For instance, tariff rates applied on products under the pollution management category range from 0%-3% in the most developed countries, but 15%-30% in many developing countries (OECD 2005). Meanwhile, the OECD member countries currently account for about 90% of the commercial market for EG, and because of high start up costs to engage in EG production, they are generally immune from competition (Baumol 1995).[2] Furthermore, over the present decade, the EG demand is expected to grow by less than 1% in developed countries, compared to 8.6% in the developing world (Environmental Business International 2002).

In this context, it remains important to ask a key question: how does this liberalization of trade in EG ultimately affect the quality of the environment and social welfare? The purpose of this paper is to approach this question by focusing on a specific scenario and answering the following set of questions. Let us suppose that an international accord states that import tariffs on a specific EG that helps to abate a non-transboundary pollutant must be cut by a given amount. How would the government regulator in a country that does not produce this EG adjust environmental taxes imposed on the pollutant? How, in turn, would these changes in trade and environmental policies affect EG prices and consumption? And finally, what would the ultimate impact of this specific type of trade liberalization be on the quality of the environment and social welfare?

To this end, we develop a two-country model of international trade in EG. In this model, an international monopolistic eco-industry offers EG to perfectly competitive pol-

[2] Of the top ten largest environmental firms, four are from the USA, two each from France and Japan, and one each from Germany and the UK (Simpson 2006). None of the world's top 50 environmental firms are, in fact, located in a developing country (Geloso Grosso 2003).

luting firms. Within this imperfectly competitive framework, we show that one cannot assert that liberalization in EG would unambiguously promote environmental protection. If a country that does not produce EG typically uses import tariffs to extract the eco-industry rents, and if these tariffs are subsequently reduced, we show that the regulator might respond by strategically setting environmental regulations that are relatively lenient. As environmental regulations become lax, the total output of polluting firms will increase. Thus, even though the prices of EG might decrease and their consumption will increase following trade liberalization, the quality of the environment might ultimately be worsened and social welfare might decrease.

Despite a series of studies on trade liberalization in EG by international organizations (WTO 2001; OECD 2001, 2005; UNCTD 2003; Bora and Teh 2004; World Bank 2007), the economic literature includes virtually no analysis of the potential effects of this trade policy reform. The linkage between environmental regulation and international trade in polluting goods has, of course, been addressed extensively in the trade and environment literature (see, e.g., Markusen 1975; Conrad 1993; Barrett 1994; Kennedy 1994; Rauscher 1994, 1997; Ulph 1997; Walz and Wellisch 1997; Copeland 2000; Long and Soubeyran 2000; Hamilton and Requate 2004). Specifically, Rauscher (1997) considers a monopolistic foreign firm which exports a polluting good into a home country. In this sense, his work is the most closely related to ours than the remaining of the above papers. However, Rauscher (1997) considers an imported good which generates pollution when being used, whereas in our model the imported good is used to abate pollution . In contrast to the theory put forward in Rauscher (1997), where environmental regulations are strengthened to shift profits from a foreign monopolist to the domestic economy, our paper argues that the presence of an imperfect competitive foreign eco-industry is a rationale for shielding domestic non-traded goods industries from stringent pollution policies. Thereby, our paper cautions policymakers against expecting an increase in pollution levels resulting from trade liberalization in EG and makes a compelling case for them to link such trade policy to environmental regulation.

Our findings also contribute to the growing body of trade and environment literature that takes into account the presence of an eco-industry (Baumol 1995; Feess and Muehlheusser 1999, 2002; Brock and Boadu 2004; Carpentier, Gallagher, and Vaughan 2005; Copeland 2005; Canton 2007; Dijkstra and Mathew 2008; Greaker 2006; Greaker and Rosendahl 2008). Within this body of work, the closest to ours are Canton (2007) and Dijkstra and Mathew (2008). Canton (2007) compares optimal pollution taxes in two countries that have different abilities to produce EG. Among other things, he shows that the optimal emission tax in the net importing country of EG will be higher in the presence of segmented markets than in the case of a world market. Based on this result, he conjectures that the environmental benefits of liberalization in EG are uncertain. However, he does not explicitly analyze, as we do, the ultimate consequences of liberalization on EG consumption and on the quality of the environment.

Dijkstra and Mathew (2008) analyze the environmental impact of liberalization in EG. They also argue that pollution may increase following trade liberalization in EG. However, their work differs from ours in several ways. First, they examine effects resulting from the transition from autarky to free trade in EG. Second, unlike the current paper, they consider trading countries that, although they may do so with different efficiencies, can both produce EG. Third, they model the relationship between the polluting industry and the eco-industry as consisting of a transfer, at a flat fee, of a more efficient abatement technology, which is the outcome of environmental research and development (R&D). As a consequence, they interpret their results as stemming from how liberalization affects the incentives of eco-industries to conduct R&D. In contrast, we highlight imperfect competition within the eco-industry as well as the interaction between environmental and EG trade policies as the main explanations of our findings.

The remainder of this paper is structured as follows. Section 2 develops our model of international trade in EG. Section 3 derives optimal emission taxes in both the exporting and importing countries. Section 4 analyzes the effects of liberalization. Section 5 provides a numerical illustration of our results. Final comments and suggestions for future research are provided in the concluding section.

2. The model

Let us frame our model around two countries: a domestic country, denoted hereafter by the subscript h (h for home), and a foreign country, which we denote by the subscript f (f for foreign). Suppose that eco-industrial activities are technologically or financially unviable in the domestic country, and consider an international monopolistic eco-industry that is owned and located in the foreign country.

The foreign eco-industry produces a homogeneous environmental good (EG) that is sold in both the domestic and foreign countries. We denote by a_h and a_f the amount of EG that the eco-industry sells in the domestic and the foreign country, respectively. This eco-industry has a cost function denoted by $g\left(a_h + a_f\right)$, where $g > 0$.[3] We assume that trade in EG occurs with zero transportation and adaptation cost. We also assume that the domestic and foreign markets of EG are segmented. These markets are composed of local polluting firms that purchase EG to abate pollution associated with their production process.

In both countries, polluting firms produce a homogenous consumption good within a local perfectly competitive market. In other words, polluting firms do not compete in the international market. Throughout, we also assume that pollution is non-transboundary. Moreover, in line with previous papers dealing with environmental outsourcing (David and Sinclair-Desgagné 2005; Nimubona and Sinclair-Desgagné 2005; Canton 2007; Canton, Soubeyran, and Stahn 2008; David, Nimubona, and Sinclair-Desgagné 2008), we consider that polluting firms proceed with an end-of-pipe pollution abatement. Therefore, the representative polluting firm's emission level in country i - with $i = h, f$ - is given by the following additively separable function: $e_i(x_i, a_i) = w\left(x_i\right) - \epsilon\left(a_i\right)$, where a_i is the total demand for EG and x_i is the total output of the polluting industry. We assume this emission function to be twice continuously differentiable: $w'\left(x_i\right) > 0$ (production

[3] The linear EG production costs function allows us to separate the eco-industry's decisions in the domestic and foreign environmental markets.

generates pollution), $w''(x_i) \geqslant 0$ (increasing marginal pollution), $\epsilon'(a_i) > 0$ (abatement effort reduces pollution), and $\epsilon''(a_i) < 0$ (decreasing returns to abatement).

A benevolent regulator in country i introduces an emission tax t_i to tackle the pollution problem. In the presence of such an environmental policy, the local market for the EG is characterized by the following inverse demand function: $p_i(a_i, t_i)$ where p_i and a_i respectively stand for the price and total demand for EG in country i. To ensure the existence and uniqueness of the solution for the eco-industry's problem, we assume that $2\frac{\partial p_i}{\partial a_i} + a_i \frac{\partial^2 p_i}{(\partial a_i)^2} < 0$. On the other hand, the domestic country, which imports EG, has incentives to extract rents from the monopolistic eco-industry by imposing a specific trade tariff τ on its imports of EG.[4] For simplicity, we assume that this tariff barrier is exogenously determined.

We are ultimately interested in how an exogenous reduction of the import tariff would affect the quality of the environment as well as social welfare in the domestic country. This can be interpreted as the outcome of a four-stage game. In the first stage, governments of the domestic and foreign countries agree upon an exogenous reduction of the EG import tariff. In the second stage, national regulators in both countries set their optimal emission taxes. In the third stage, the eco-industrial firm determines the quantities of EG that will be supplied to polluting industries in both countries. In the last stage, these polluting firms express their demand for EG while competing locally to supply the final good.

[4] For more details about the intuition behind rents extraction through tariff revenues, see Katrak (1977), Svedberg (1979), Brander and Spencer (1981, 1984), Tower (1983), Dixit (1984), Hillman and Templeman (1985), Rauscher (1997), among others. Along the same line, Bergstrom (1982) argues that an excise tax can capture oil rents from foreign suppliers.

3. The emission taxes

Emission taxes result from the three last stages in our game. As usual, let us solve the game backwards beginning with the behavior of polluting industries.

3.1. The behavior of polluting industries

Let $C(x_i)$ be the production cost function of a representative polluting firm in country i. This cost function is assumed to be strictly increasing ($C'(x_i) > 0$) and convex ($C''(x_i) > 0$). In the presence of an emission tax, the polluting firm will choose the level of demand for EG and supply of the final good that will maximize its profit. This profit is given by the following function:

$$\Pi_i(x_i, a_i) = P_i x_i - C(x_i) - p_i a_i - t_i [w(x_i) - \epsilon(a_i)] \ ,$$

where P_i is the current price of the final good. To maximize its profit, the representative polluter sets its marginal revenue and the cost of pollution abatement equal to, respectively, its marginal cost of production and the benefit of pollution abatement, i.e.

$$P_i = C'(x_i) + t_i w'(x_i) \ , \quad (1)$$

$$p_i = t_i \epsilon'(a_i) \ . \quad (2)$$

Expression (2) yields the inverse demand function for EG. This inverse demand function is downward sloping ($\frac{dp_i}{da_i} = t_i \epsilon''(a_i) < 0$). Moreover, as pointed out by David and

Sinclair-Desgagné (2005) and Requate (2005), any change in the level of the emission tax t_i has two distinct effects on the pollution abatement demand curve: a shift effect $\left(\left.\frac{dp_i}{dt_i}\right|_{a_i} = \epsilon'(a_i) > 0\right)$ and a rotation effect $\left(\frac{\partial^2 p_i}{\partial a_i \partial t_i} = \epsilon''(a_i) < 0\right)$. The shift effect means that the polluters' willingness to buy EG increases with the stringency of the emission tax. The rotation effect in turn means that the price-sensitivity of the pollution abatement demand decreases with the stringency of the emission tax. This leads us to the analysis of the behavior of the eco-industry.

3.2. The behavior of the eco-industry

To determine its optimal supplies of EG to the domestic and foreign countries, the eco-industry solves the following program:

$$\underset{a_h, a_f}{Max} \qquad \Pi_f = [p_h(a_h, t_h) - \tau]\, a_h + p_f(a_f, t_f)\, a_f - g(a_h + a_f).$$

At the point of equilibrium, the behavior of the eco-industry is thus characterized by the following set of equations:

$$\frac{\partial \Pi_f}{\partial a_h} = p_h(a_h, t_h) + \frac{\partial p_h}{\partial a_h} a_h - \tau - g = 0, \tag{3}$$

$$\frac{\partial \Pi_f}{\partial a_f} = p_f(a_f, t_f) + \frac{\partial p_f}{\partial a_f} a_f - g = 0. \tag{4}$$

These first-order conditions for profit maximization yield the following solutions for the output of the monopolistic eco-industry: $a_h^* = a_h(t_h, \tau)$ and $a_f^* = a_f(t_f)$. The latter solutions correspond to the equilibrium quantities of EG supplied to the domestic and foreign market, respectively. They suggest that the national emission tax affects the equilibrium consumption of EG in each country. However, only the consumption of EG in the domestic country depends on the level of the import tariff. We show below how benevolent regulators account for this, while choosing optimal emission taxes.

3.3. The optimal emission taxes

In each country, the regulator chooses the emission tax that maximizes local social welfare. The latter is defined as the sum of consumer surplus for the final good, the polluting industry's profits, government's tax revenues, and either eco-industry's profits or government's tariff revenues, less the social damage due to pollution. Let v be the marginal social damage of pollution. Assuming there is no cost associated with the transfer of public funds, regulators in the domestic and foreign countries thus solve the following programs, respectively:

$$\underset{t_h}{Max} \qquad W_h = \int_0^{x^h} P_h(z)\,dz - C(x_h) + [\tau - p_h(a_h, t_h)]\,a_h - v\,[w(x_h) - \epsilon(a_h)] \ , \qquad (5)$$

$$\underset{t_f}{Max} \qquad W_f = \int_0^{x_f} P_f(z)\,dz - C(x_f) + [p_h(a_h, t_h) - \tau]\,a_h - g(a_h + a_f) - v\,[w(x_f) - \epsilon(a_f)] \ . \qquad (6)$$

Solving (5) with respect to t_h and (6) with respect to t_f (computational details are provided in appendix C) gives the following expressions of optimal emission taxes for the domestic and foreign country, respectively:

$$t_h = v + \frac{a_h \frac{dp_h}{dt_h} - \tau \frac{da_h}{dt_h}}{w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h}}, \tag{7}$$

$$t_f = v + \frac{a_f \frac{\partial p_f}{\partial a_f}\frac{da_f}{dt_f}}{w'(x_f)\frac{dx_f}{dt_f} - \epsilon'(a_f)\frac{da_f}{dt_f}}. \tag{8}$$

The first term on the right hand side of both expressions (7) and (8) corresponds to the Pigouvian rate, that is, the marginal social damage of pollution. The denominator of the second term on the right hand side of both (7) and (8) is negative (from the results of standard comparative statics in appendices A and B.1., as well as our assumptions). It represents the marginal effect of the tax on total emissions. The numerator of the second term on the right hand side of expression (8) of the emission tax in the foreign country is also negative. In line with David and Sinclair-Desgagné (2005), Requate (2005), and Canton (2007), the optimal emission tax in the foreign country is therefore higher than the Pigouvian rate. The intuition for this result is as follows. Because of the monopolistic behavior of the eco-industry, prices of EG will generally be higher than their marginal cost of abatement. To encourage local polluters to abate pollution up to an efficient level, the regulator must give them strong incentives in the form of an emission tax higher than the social marginal damage of pollution.

The numerator of the second term on the right hand side of expression (7) of the emission tax in the domestic country, however, comprises two new components. The first component ($a_h \frac{dp_h}{dt_h}$) depends on the effect of the emission tax on the equilibrium price of EG in the domestic country. For not sufficiently convex abatement demand functions, including linear and concave demand functions, we have that $\frac{dp_h}{dt_h} > 0$ (see details in appendix B.2). Therefore, in the presence of a monopolistic eco-industry, an increase in the emission tax may increase the gap between the price and the marginal production cost of EG. Put another way, in the domestic country, a more stringent emission tax may increase the marginal rent paid to the foreign eco-industry. This has a negative effect on social welfare.

Consequently, the domestic country has an incentive to capture some of this rent using, for example, an import tariff on EG. This incentive transpires through the second component ($-\tau \frac{da_h}{dt_h}$) of the numerator in (7). From appendix B.1., we have that $\frac{da_h}{dt_h} > 0$, that is, the import demand for EG increases with the emission tax. In the presence of a positive import tariff ($\tau > 0$), tariff revenues thus increase with the tax.[5] From this perspective, a more stringent emission tax will result in improved social welfare. This second component shows that the optimal emission tax in the domestic country depends on the tax-sensitivity of tariff revenues.

Therefore, the sign of $(t_h - v)$ obviously depends on the level of τ, the import tariff

[5] Although a tariff on EG is attractive from the point of view of the domestic country, tariff revenues generated are, of course, somewhat offset by a distortionary loss related to the presence of the import tariff. This loss is implicitly accounted for in the social welfare function.

on EG. When τ is significantly high, the tariff revenue effect of the emission tax is likely higher in absolute value than its price effect. As a consequence, the optimal emission tax in the domestic country is higher than the Pigouvian rate, a finding which amends the result in Canton (2007).[6] Conversely, when τ is significantly low or equal to zero and if $\frac{dp_h}{dt_h} > 0$, we retrieve the result in Canton (2007) of an optimal emission tax lower than the Pigouvian tax. All these findings are summarized in the following proposition.

Proposition 1. *In a country that relies exclusively on environmental goods imported from a monopolistic eco-industry to abate its pollution, the optimal emission tax may be lower than, equal to, or greater than the Pigouvian rate, depending on its relative effect on the price of these environmental goods and the tariff revenues generated from importation. When a high import tariff is imposed on environmental goods, for example, the tariff revenue effect will likely overcome the price effect, in which case the optimal emission tax must be higher than the Pigouvian rate.*

This indicates that EG import tariffs must interact with emission taxes in the domestic country. The following section looks at this issue in more detail. We initially study the net impact of liberalization on the optimal emission tax, the equilibrium price, and the consumption of EG in the domestic country. This helps us to ultimately assess the impact of liberalization in EG on the quality of the environment. Given that the EG production costs function is linear, trade liberalization in EG does not affect the emission tax structure

[6] In our model, the optimal emission tax in an EG importing country is also higher than the Pigouvian rate when $\frac{dp_h}{dt_h} < 0$, that is, a tighter emission tax induces a decrease in the equilibrium price of EG.

and the consumption of EG in the foreign country, and thus it does not affect the quality of its environment.

4. The effects of trade liberalization

As just pointed out, expression (7) already suggests that import tariff variations affect the optimal structure of emission taxes in the domestic country. However, our analysis needs to consider how other variables in our model also react to tariff variations.

Let us first examine how an exogenous reduction in the import tariff rate would affect the emission tax and EG consumption. Comparative static analysis (computations are provided in appendix D) from expressions (3) and (7) yields the following:

$$\frac{dt_h}{d\tau} = \frac{\left[2\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2}\right]\frac{da_h}{dt_h} - \left[\frac{\partial p_h}{\partial t_h} + a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h} + (t_h - v)\epsilon''(a_h)\frac{da_h}{dt_h}\right]}{-\left[2\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2}\right]\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h} + (t_h - v)w''(x_h)\left(\frac{dx_h}{dt_h}\right)^2\right] - \left(\frac{\partial p_h}{\partial t_h} + a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h}\right)\left[\frac{\partial p_h}{\partial t_h} + a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h} + (t_h - v)\epsilon''(a_h)\frac{da_h}{dt_h}\right]}, \tag{9}$$

$$\frac{da_h}{d\tau} = \frac{-\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h}\right] - (t_h - v)w''(x_h)\left(\frac{dx_h}{dt_h}\right)^2}{-\left[2\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2}\right]\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h} + (t_h - v)w''(x_h)\left(\frac{dx_h}{dt_h}\right)^2\right] - \left(\frac{\partial p_h}{\partial t_h} + a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h}\right)\left[\frac{\partial p_h}{\partial t_h} + a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h} + (t_h - v)\epsilon''(a_h)\frac{da_h}{dt_h}\right]}. \tag{10}$$

When $t_h < v$,[7] the denominator of both expressions (9) and (10) is always negative. Based on our assumptions, the numerator of expression (9) is also negative. Therefore, $\frac{dt_h}{d\tau} > 0$, which implies that the emission tax and import tariff on EG vary in the same direction. This constitutes our second proposition.

[7] Recall that $t_h < v$ when $\frac{dp_h}{dt_h} > 0$ or $\tau \frac{da_h}{dt_h} - a_h \frac{dp_h}{dt_h} < 0$, that is, the equilibrium price of EG increases with the emission tax or the import tariff on EG will not be high enough to allow the domestic country to entirely extract the increase, induced by a tighter emission tax, in the eco-industry rents.

Proposition 2. *When a country fully relies on environmental goods imported from a monopolistic eco-industry, and if their equilibrium price increases with the emission tax or the import tariff on them is not high enough to successfully extract rents from the eco-industry, then trade liberalization in environmental goods gives rise to a less stringent optimal emission tax.*

In contrast to the WTO and OECD positions, which single out trade liberalization in EG as a means to induce stricter environmental regulations in countries that do not produce EG, this proposition suggests a potential reason to keep EG import tariffs in place. EG import tariffs give incentives to countries that import EG to set ambitious targets, because this increases their tariff revenues.

Another expectation is that EG consumption would increase as trade barriers fall. The sign of the numerator in expression (10) is always positive, which implies that $\frac{da_h}{d\tau} < 0$. This shows that despite the decrease in the stringency of the emission tax, EG consumption in the domestic country increases when the EG import tariff decreases. This outcome supports the call for trade liberalization in EG for its potential benefits in increasing access to EG.

To fully understand the forces contributing towards this increase in EG consumption along with the process of trade liberalization, we also analyze the effects of the latter on the equilibrium price of EG. From equation (3), we can show that

$$\frac{dp_h}{d\tau} = -\left[\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2}\right] \frac{da_h}{d\tau} - a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h} \frac{dt_h}{d\tau} + 1 \ . \tag{11}$$

According to our above results and from our assumptions, we conclude that

$$\frac{dp_h}{d\tau} \gtreqless 0 \Leftrightarrow 1 - a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h} \frac{dt_h}{d\tau} \gtreqless \left[\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2} \right] \frac{da_h}{d\tau} \ . \tag{12}$$

Hence, liberalization in EG may induce either an increase *or* a decrease in EG prices. The outcome notably depends on the curvature of the inverse demand function for EG. When $\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2} < 0$ (for instance, when the inverse demand function is linear or concave), it may happen that $1 - a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h} \frac{dt_h}{d\tau} < \left[\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2} \right] \frac{da_h}{d\tau}$. In this context, a reduction in the import tariff on EG induces an increase in its price. This increase in the EG price is more plausible when the emission tax does not significantly adjust downward following trade liberalization, when the import demand for EG increases significantly with tariff reductions, and/or when the emission tax does not significantly affect the price-elasticity of EG demand. Conversely, when $\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2} > 0$, which is possible only when the inverse abatement demand function is convex, trade liberalization always induces a decrease in the price of EG. Taken together, these observations yield our third proposition.

Proposition 3. *When environmental goods are imported from a monopolistic eco-industry, their consumption always increases as the trade tariff on them falls. Moreover, their price will decrease following liberalization if* $1 - a_h \frac{\partial^2 p_h}{\partial a_h \partial t_h} \frac{dt_h}{d\tau} > \left[\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2} \right] \frac{da_h}{d\tau}$*, a situation which is always true when* $\frac{\partial p_h}{\partial a_h} + a_h \frac{\partial^2 p_h}{(\partial a_h)^2} > 0$*. Otherwise, the price of environmental goods will increase.*

This proposition confirms that trade liberalization in EG is a viable means of promoting the growth of environmental markets. It suggests that eco-industrial firms and exporting countries of EG unambiguously benefit from the globalization of environmental markets. This is particularly true when the price of EG increases following liberalization.

In spite of this increase in EG consumption, however, improvement in environmental protection is not guaranteed in the domestic country, since the stringency of the emission tax decreases with trade liberalization:

$$\frac{de_h\left(x_h,a_h\right)}{d\tau} \gtreqless 0 \Longleftrightarrow w'\left(x_h\right)\frac{dx_h}{dt_h}\frac{dt_h}{d\tau} \gtreqless \epsilon'\left(a_h\right)\frac{da_h}{d\tau}. \qquad (13)$$

According to condition (13), total emissions in the domestic country may increase, decrease, or remain unchanged as tariff reductions occur. After some algebra, the above condition writes as follows:

$$\frac{de_h\left(x_h,a_h\right)}{d\tau} \gtreqless 0 \Longleftrightarrow x_h w'\left(x_h\right)\eta_{x\tau} \gtreqless a_h\epsilon'\left(a_h\right)\eta_{a\tau}\ , \qquad (14)$$

where $\eta_{x\tau}$ and $\eta_{a\tau}$ are the elasticities of final good production and EG consumption with respect to the EG import tariff. The impact of trade tariff cuts on the quality of the environment, therefore, depends on the relative contribution to the total emissions of the polluting output and EG consumption, as well as their relative elasticities with respect to the import tariff on EG. This important finding is captured in the next proposition.

Proposition 4. *In a country that does not produce environmental goods, the quality of the environment may either improve or worsen following trade liberalization in environ-*

mental goods. For example, when the contribution in the total emissions of the polluting output matters relatively more than that of the environmental goods consumption, and/or the elasticity of polluting output with respect to the EG import tariff is relatively higher than that of EG consumption, total emissions increase as the EG import tariff falls.

This proposition suggests that the potential benefits of EG tariff reductions to promote environmental protection in EG importing countries may not occur, since their environmental regulations would become less stringent. Actually, a lower emission tax, which results from a decrease in the import tariff, has two effects. First, the demand for EG falls because it is cheaper to pollute and pay the emission tax than to abate at the margin. Second, the quantity of polluting goods -and hence total emissions- rise because it is cheaper to produce the polluting good and then pollute at the margin. Of course, as we have already shown, the decrease in the import tariff rate may also lower the price of EG in the domestic country, which may reduce the cost of abating pollution and increases EG consumption. However, if the two former effects dominate, it is possible that total emissions increase with a reduction in the tariff rate.

Finally, let us now predict the welfare impact of EG trade liberalization when the emission tax is lower than the marginal social cost of pollution, which is generally the case in many developing countries. A change in the EG tariff τ results in the following welfare change (see details in appendix D)

$$\frac{dW_h}{d\tau} = (t_h - v)\, w'(x_h) \frac{dx_f}{d\tau} + v\epsilon'(a_h) \frac{da_h}{d\tau} + [\tau - p_h(a_h, t_h)] \frac{da_h}{d\tau} + a_h \left(1 - \frac{dp_h}{d\tau}\right). \quad (15)$$

The net welfare effect of EG trade liberalization is ambiguous. It is determined by four effects which have different signs. The first effect, which corresponds to the increase in non-internalized environmental damage, is welfare reducing. The second effect is welfare improving as it corresponds to the value of the decrease in environmental damage. The last two effects measure the change in revenues shifted from the eco-industry, and they can be either welfare improving or welfare reducing. Their signs respectively depend on how the actual level of the import tariff compares to the equilibrium price of EG, and on how the latter reacts to tariff reductions. Our last proposition summarizes conditions under which EG trade liberalization reduces social welfare.

Proposition 5. *Suppose the emission tax is lower than the marginal social cost of pollution ($t_h < v$). Then, assuming that the actual level of the EG import tariff is lower than the EG equilibrium price ($\tau < p_h$), and that the latter price increases with trade liberalization ($\frac{dp_h}{d\tau} < 0$), an EG-importing country will be worse off following EG trade liberalization when the positive environmental effect of this trade policy is not large enough to overturn its negative environmental and rent extraction effects.*

The above proposition highlights, once again, the profit-shifting role of the EG tariff. In fact, EG trade liberalization increases revenues of the eco-industry while decreasing the EG-importing country's tariff revenues. As the two first propositions suggest, it is possible to decrease the emission tax to slow down the flow of revenues from the importing country toward the foreign eco-industry. However, as the emission tax decreases, the production of the polluting good increases. Therefore, even though EG consumption would increase following EG trade liberalization, the net effect of this trade policy may be a decrease in social welfare.

5. A numerical example

Let us now illustrate our results with a numerical example so as to completely characterize the effects of trade liberalization in EG. Our numerical example uses the following specific functions. $P_h = 30 - x_h$ is the demand for the polluting good. $C(x_h) = \frac{1}{2}x_h^2$ corresponds to the polluting good production costs, and $e_h(x_h, a_h) = x_h - \left(4a_h - \frac{1}{2}a_h^2\right)$ is the total emissions function. Next, $G(a_h) = 5a_h$ represents the EG production costs function. Finally, the parameter value of the social marginal pollution damage is $v = 20$.

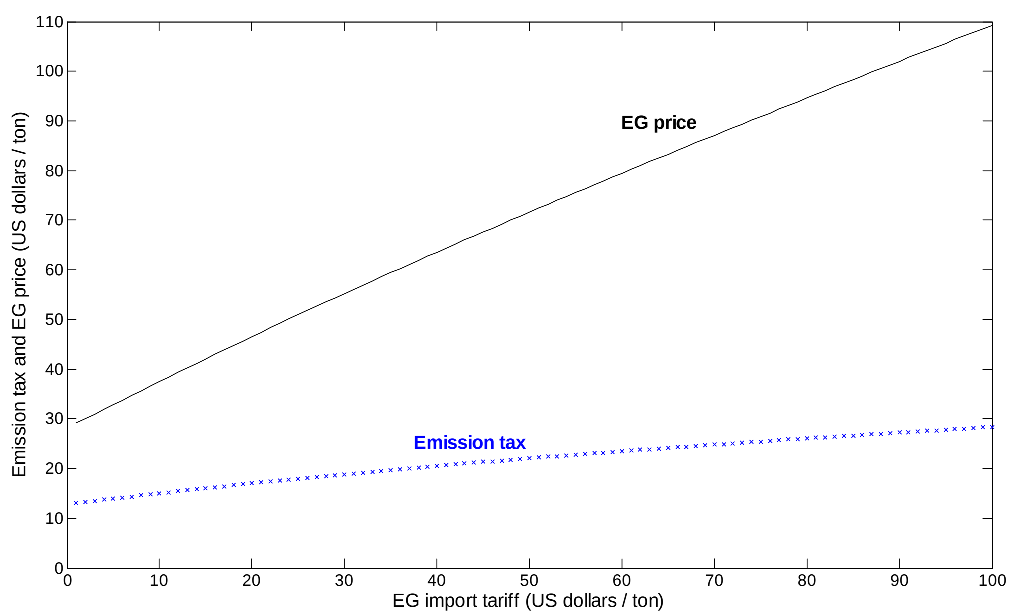

Figure 1: Emission tax and EG price.

Figure 1 represents the evolution of the emission tax and the equilibrium price of EG when the import tariff on EG varies. Our simulations confirm our result that the emission tax decreases following an exogenous EG import tariff cut. They also reveal that the equilibrium EG price decreases when the import tariff falls. In this case, we can therefore confirm that the forces that induce a decrease in the price of EG (i.e. the reduction in the distortion related to the import tariff and the decrease in the emission tax) dominate the increasing effect from a higher EG demand.

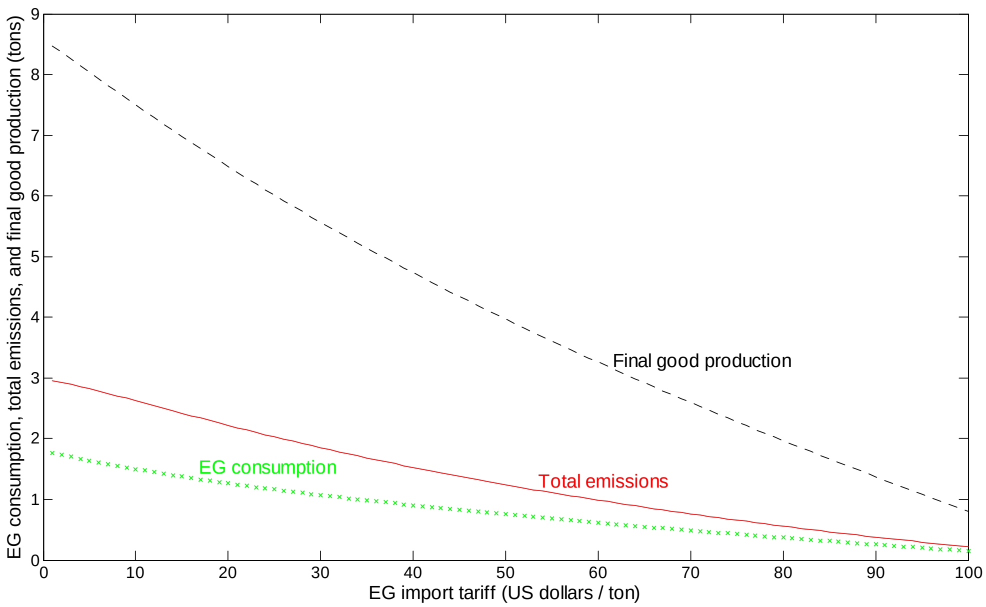

Figure 2: EG consumption, total emissions, and final good production.

Figure 2, in turn, shows how the polluting good production, EG consumption, and total emissions evolve when trade liberalization occurs. From this figure, we can see that EG consumption as well as the polluting output increase as a consequence of trade liberalization. The fall of tariff barriers, however, results in an increase in total emissions.

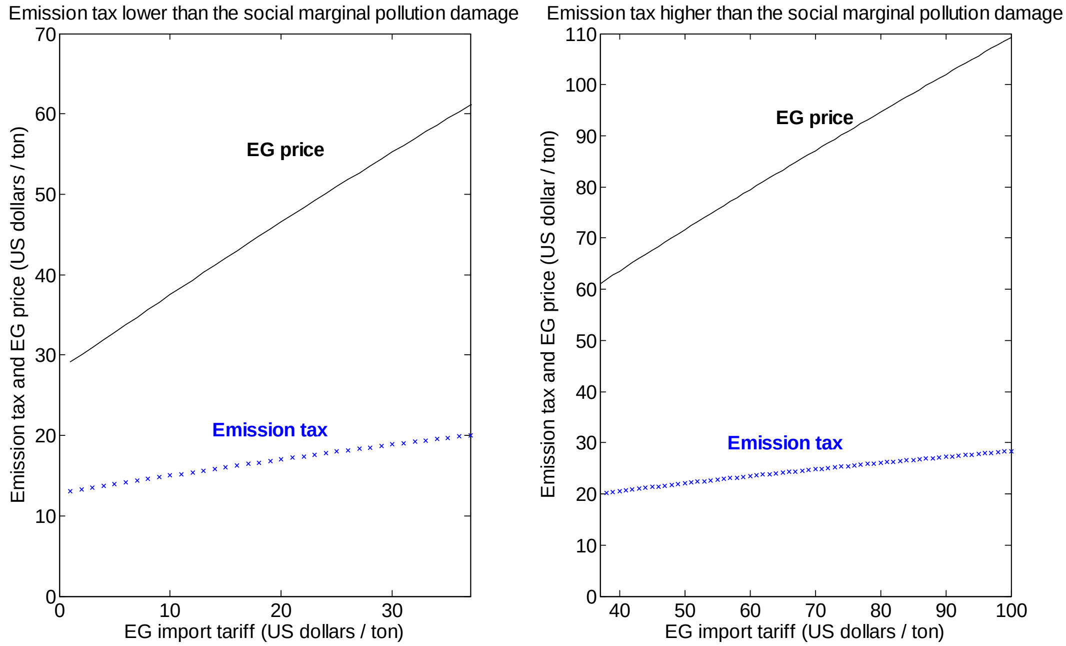

Figure 3: Emission tax and EG price: $t_h < v$ versus $t_h > v$.

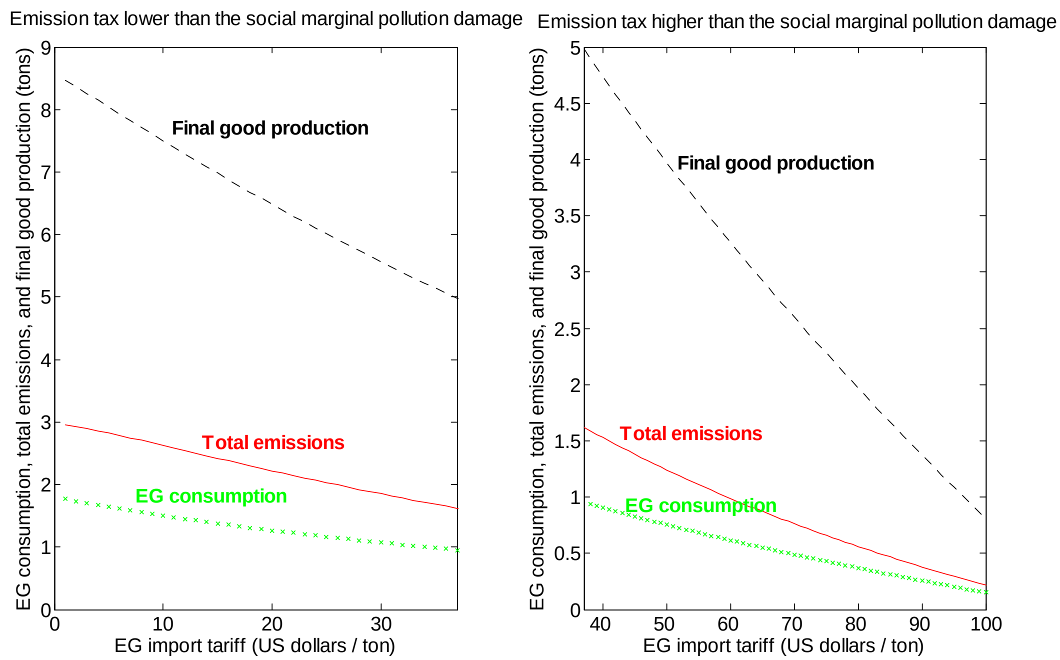

Figure 4: EG consumption, total emissions, and final good production: $t_h < v$ versus $t_h > v$.

Figures 3 and 4 compare our results in two specific cases: when $t_h < v$ and when $t_h > v$. Recall that we are not able to sign expressions (9) and (10) in the latter case. When $t_h < v$, the conclusions from our analytical results are confirmed. Interestingly, when $t_h > v$, we see now the very same trends for the emission tax, the EG consumption, the EG price, the pollution output, and total emissions as when $t_h < v$.

As we pointed out in the analysis of our analytical results, total emissions do not, of course, always increase when trade liberalization occurs. The above results simply illustrate our finding that total emissions increase following liberalization in EG when the impact on pollution of the underlying increase in the polluting output outweighs that of the increase in EG consumption. This is likely the case when marginal pollution from the final good production is significantly high. Should marginal pollution be significantly low, the outcome of trade liberalization in EG may in fact be a decrease in total emissions.[8]

6. Concluding remarks

Inasmuch as trade liberalization decreases prices of imported goods, lower barriers to trade in EG would translate into greater access to the most efficient, diverse, and least expensive EG in countries that do not produce them. This, in turn, would encourage local governments to set more ambitious environmental objectives. At least, this is what one would expect. This paper argues, however, that the actual outcome of trade liberalization in EG is less straightforward. Our results show that EG tariff reductions give rise to a

[8]Numerical results that support this figure are available from the author upon request.

less stringent emission tax and more imports of EG. Nevertheless, the total output of polluting firms increases as a result of the laxer environmental regulation, leading to a potential rise in pollution. As a consequence, EG-importing countries might be worse off when the welfare improving effect of EG trade liberalization, stemming from the increase in EG consumption, is not large enough to compensate for the negative effects of this trade policy.

The market power that international eco-industrial firms enjoy is the centrepiece of this interplay between EG trade and environmental policies. Indeed, stringent environmental regulation generates rents for an imperfectly competitive eco-industry. Therefore, when an import tariff on EG cannot sufficiently extract these rents, the government regulator in an EG-importing country strategically lessens the stringency of environmental regulation to maximize domestic social welfare.

Our findings provide policy-makers with insights regarding the main conditions under which trade liberalization in EG would succeed in improving environmental performance throughout the world. First, getting rid of the market power that the eco-industry enjoys is key to ensuring that this trade reform benefits those countries that rely on external suppliers of EG. Unfortunately, EG-importing countries that would benefit from more competition in the eco-industry do not have much influence in that sphere. Second, the potential role of EG trade tariffs to extract rents from the eco-industry must be recognized. Given that trade tariffs are an easy way to collect revenues, it becomes particularly difficult to admit that EG import tariffs should be lowered in developing countries, which generally have trouble collecting taxes. Third, the underlying connection between environmental, industrial, and EG trade policies should be considered in the setting of international trade agreements targeting EG.

Several interesting dimensions of this issue have not been addressed by our analysis. First, although connections exist between trade in environmental goods and trade in environmental services, this paper has focused solely on environmental goods. Thus, specific issues related to trade liberalization in environmental services remain to be analyzed.[9] Second, we have ignored the foreign direct investments inducement by EG tariff barriers. In fact, eco-industrial firms create subsidiaries in host countries for most of their contracts abroad (Steenblik, Drouet, and Stubbs 2005). How this situation relies on the presence of tariff barriers to trade in EG still needs to be examined. Third, since the level of import tariffs are in reality endogenously determined, an analysis of the optimal combination of EG trade and environmental policies would be of particular interest. Fourth, it would be useful to compare the results of marginal and non-marginal trade liberalization. Fifth, our analysis could be extended to verify whether trade liberalization in EG aimed at dealing with transboundary pollution abatement would have the same environmental effect as that demonstrated in this paper.[10] Finally, eco-industry representatives often present

[9] For instance, while tariffs constitute the main trade barrier on environmental goods, they are not applied to environmental services. On the services side, potential barriers include everything else that can inhibit trade: allowing exports of services only through firms with commercial presence in the importing country, limiting the scope of foreign business to specified activities, etc. (OECD 2005).

[10] To this end, our model would be amended by specifying pollution damage functions that depend upon emissions levels in both countries. Intuitively, the quality of the environment in the foreign country is in this case also affected by trade liberalization in environmental goods. As a consequence, regulators in both countries have incentives to coordinate their efforts to deal with market distortions that exist in the eco-industry.

the globalization of environmental markets as a stimulus of mergers and acquisitions in this industry. Since this would give rise to a more concentrated and (market) powerful eco-industry, which is central to the environmental impact of trade liberalization in EG, it would be interesting to analyze the interplay between trade policy targeting EG, environmental policy, and mergers' activities in the eco-industry. These are some of the issues left for further research.

Appendices

A. Comparative-static analysis for the polluting industry

Differentiating equations (1) and (2) with respect to t_i yields:

$$-C''(x_i)\frac{dx_i}{dt_i} - t_i w''(x_i)\frac{dx_i}{dt_i} = w'(x_i),$$

$$-t\epsilon''(a_i)\frac{da_i}{dt_i} = \epsilon'(a_i).$$

Solving this set of equations by Cramer's rule gives us the following results:

$$\frac{dx_i}{dt_i} = -\frac{w'(x_i)}{C''(x_i)+t_i w''(x_i)},$$

$$\frac{da_i}{dt_i} = -\frac{\epsilon'(a_i)}{t\epsilon''(a_i)}.$$

From our assumptions, we have that $\frac{dx_i}{dt_i} < 0$ and $\frac{da_i}{dt_i} > 0$.

B. Comparative-static analysis for the eco-industry

B.1. Impact of environmental taxation on the equilibrium supply of EG

Differentiating equation (3) with respect to t_h and equation (4) with respect t_f respectively gives

$$2\frac{\partial p_h}{\partial a_h}\frac{da_h}{dt_h}+\frac{\partial p_h}{\partial t_h}+a_h\frac{\partial^2 p_h}{(\partial a_h)^2}\frac{da_h}{dt_h}+a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h}=0,$$
$$2\frac{\partial p_f}{\partial a_f}\frac{da_f}{dt_f}+\frac{\partial p_f}{\partial t_f}+a_f\frac{\partial^2 p_f}{\left(\partial a_f\right)^2}+a_f\frac{\partial^2 p_f}{\partial a_f \partial t_f}=0.$$

This implies that

$$\frac{da_h}{dt_h}=-\frac{\frac{\partial p_h}{\partial t_h}+a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h}}{2\frac{\partial p_h}{\partial a_h}+a_h\frac{\partial^2 p_h}{(\partial a_h)^2}}$$
$$\frac{da_f}{dt_f}=-\frac{\frac{\partial p_f}{\partial t_f}+a_f\frac{\partial^2 p_f}{\partial a_f \partial t_f}}{2\frac{\partial p_f}{\partial a_f}+a_f\frac{\partial^2 p_f}{\left(\partial a_f\right)^2}}.$$

Our assumptions imply that $\frac{da_h}{dt_h}>0$ and $\frac{da_f}{dt_f}>0$.

B.2. Impact of environmental taxation on the equilibrium price of EG

From equations (3) and (4), we have that

$$\frac{dp_h}{dt_h}=-\left[\frac{\partial p_h}{\partial a_h}+a_h\frac{\partial^2 p_h}{(\partial a_h)^2}\right]\frac{da_h}{dt_h}-a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h},$$
$$\frac{dp_f}{dt_f}=-\left[\frac{\partial p_f}{\partial a_f}+a_f\frac{\partial^2 p_f}{\left(\partial a_f\right)^2}\right]\frac{da_f}{dt_f}-a_f\frac{\partial^2 p_f}{\partial a_f \partial t_f}.$$

This is equivalent to

$$\frac{dp_h}{dt_h}\gtreqless 0 \quad\Leftrightarrow\quad \left[\frac{\partial p_h}{\partial a_h}+a_h\frac{\partial^2 p_h}{(\partial a_h)^2}\right]\frac{da_h}{dt_h}+a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h}\lesseqgtr 0$$
$$\frac{dp_f}{dt_f}\gtreqless 0 \quad\Leftrightarrow\quad \left[\frac{\partial p_f}{\partial a_f}+a_f\frac{\partial^2 p_f}{\left(\partial a_f\right)^2}\right]\frac{da_f}{dt_f}+a_f\frac{\partial^2 p_f}{\partial a_f \partial t_f}\lesseqgtr 0.$$

From our assumptions and the results in appendix (B.1), we can show that $\frac{dp_h}{dt_h} > 0$ always if $p_h(a_h, t_h)$ is linear or concave in a_h. Similarly, $\frac{dp_f}{dt_f} > 0$ always if $p_f(a_f, t_f)$ is linear or concave in a_f.

C. Optimal emission taxes

Totally differentiating (5) with respect to t_h and (6) with respect to t_f yields, respectively

$$\frac{dW_h}{dt_h} = [P_h(x_h) - C'(x_h)]\frac{dx_h}{dt_h} - v\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h}\right] + [\tau - p_h(a_h, t_h)]\frac{da_h}{dt_h} - a_h\frac{dp_h}{dt_h} = 0, \quad \text{(C-1)}$$

$$\frac{dW_f}{dt_f} = [P_f(x_f) - C'(x_f)]\frac{dx_f}{dt_f} - g(a_h + a_f)\frac{da_f}{dt_f} - v\left[w'(x_f)\frac{dx_f}{dt_f} - \epsilon'(a_f)\frac{da_f}{dt_f}\right] = 0. \quad \text{(C-2)}$$

Substituting (1) into (C-1), and (1) and (4) into (C-2), we get, respectively

$$t_h w'(x_h)\frac{dx_h}{dt_h} - v\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h}\right] + [\tau - p_h(a_h, t_h)]\frac{da_h}{dt_h} - a_h\frac{dp_h}{dt_h} = 0, \quad \text{(C-3)}$$

$$t_f w'(x_f)\frac{dx_f}{dt_f} - \left[p_f(a_f, t_f) + a_f\frac{\partial p_f}{\partial a_f}\right]\frac{da_f}{dt_f} - v\left[w'(x_f)\frac{dx_f}{dt_f} - \epsilon'(a_f)\frac{da_f}{dt_f}\right] = 0. \quad \text{(C-4)}$$

Substituting, now, (2) into (C-3) and (C-4), we have, respectively

$$t_h w'(xh)\frac{dx_h}{dt_h} - v\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h}\right] + \tau\frac{da_h}{dt_h} - t_h\epsilon'(a_h)\frac{da_h}{dt_h} - a_h\frac{dp_h}{dt_h} = 0, \quad \text{(C-5)}$$

$$t_f w'(x_f)\frac{dx_f}{dt_f} - t_f\epsilon'(a_f)\frac{da_f}{dt_f} - a_f\frac{\partial p_f}{\partial a_f}\frac{da_f}{dt_f} - v\left[w'(x_f)\frac{dx_f}{dt_f} - \epsilon'(a_f)\frac{da_f}{dt_f}\right] = 0. \quad \text{(C-6)}$$

Solving equations (C-5) with respect to t_h and (C-6) with respect to t_f gives, respectively, expressions (7) and (8).

D. Effects of import tariff variations

Differentiating equations (3) and (7) with respect to τ gives

$$\left[2\frac{\partial p_h}{\partial a_h} + a_h\frac{\partial^2 p_h}{(\partial a_h)^2}\right]\frac{da_h}{d\tau} + \left[\frac{\partial p_h}{\partial t_h} + a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h}\right]\frac{dt_h}{d\tau} = 1,$$

$$\left[\frac{dp_h}{dt_h} + a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h} + (t_h - v)\,\epsilon''(a_h)\frac{da_h}{dt_h}\right]\frac{da_h}{d\tau} - \left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h} + (t_h - v)\,w''(x_h)\left(\frac{dx_h}{dt_h}\right)^2\right]\frac{dt_h}{d\tau} = \frac{da_h}{dt_h}.$$

Solving the above set of equations by Cramer's rule gives the following results:

$$\frac{dt_h}{d\tau} = \frac{\left(2\frac{\partial p_h}{\partial a_h} + a_h\frac{\partial^2 p_h}{(\partial a_h)^2}\right)\frac{da_h}{dt_h} - \left[\frac{\partial p_h}{\partial t_h} + a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h} + (t_h - v)\epsilon''(a_h)\frac{da_h}{dt_h}\right]}{-\left(2\frac{\partial p_h}{\partial a_h} + a_h\frac{\partial^2 p_h}{(\partial a_h)^2}\right)\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{da_h}{dt_h} + (t_h - v)w''(x_h)\left(\frac{dx_h}{dt_h}\right)^2\right] - \left(\frac{\partial p_h}{\partial t_h} + a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h}\right)\left[\frac{dp_h}{dt_h} + a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h} + (t_h - v)\epsilon''(a_h)\frac{da_h}{dt_h}\right]},$$

$$\frac{da_h}{d\tau} = \frac{-\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{dA_h}{dt_h}\right] - (t_h - v)w''(x_h)\left(\frac{dx_h}{dt_h}\right)^2}{-\left(2\frac{\partial p_h}{\partial a_h} + a_h\frac{\partial^2 p_h}{(\partial a_h)^2}\right)\left[w'(x_h)\frac{dx_h}{dt_h} - \epsilon'(a_h)\frac{dA_h}{dt_h} + (t_h - v)w''(x_h)\left(\frac{dx_h}{dt_h}\right)^2\right] - \left(\frac{\partial p_h}{\partial t_h} + a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h}\right)\left[\frac{dp_h}{dt_h} + a_h\frac{\partial^2 p_h}{\partial a_h \partial t_h} + (t_h - v)\epsilon''(a_h)\frac{da_h}{dt_h}\right]}.$$

Now, totally differentiating (5) with respect to τ yields

$$\frac{dW_h}{d\tau} = \left[P_h\left(x_h\right) - C'\left(x_h\right)\right]\frac{dx_h}{d\tau} - v\left[w'\left(x_h\right)\frac{dx_h}{d\tau} - \epsilon'\left(a_h\right)\frac{da_h}{d\tau}\right] + \left[\tau - p_h(a_h, t_h)\right]\frac{da_h}{d\tau} + a_h\left(1 - \frac{dp_h}{dt_h}\right) = 0. \quad \text{(D-1)}$$

Substituting (1) into (D-1), we get

$$\frac{dW_h}{d\tau} = t_h w'\left(x_h\right)\frac{dx_h}{d\tau} - v\left[w'\left(x_h\right)\frac{dx_h}{d\tau} - \epsilon'\left(a_h\right)\frac{da_h}{d\tau}\right] + \left[\tau - p_h(a_h, t_h)\right]\frac{da_h}{d\tau} + a_h\left(1 - \frac{dp_h}{d\tau}\right) = 0, \quad \text{(D-2)}$$

which also corresponds to

$$\frac{dW_h}{d\tau} = \left(t_h - v\right)w'\left(x_h\right)\frac{dx_f}{d\tau} + v\epsilon'\left(a_h\right)\frac{da_h}{d\tau} + \left[\tau - p_h(a_h, t_h)\right]\frac{da_h}{d\tau} + a_h\left(1 - \frac{dp_h}{d\tau}\right). \quad \text{(D-3)}$$

Finally, differentiating equation (1) with respect to τ for $i = h$ yields:

$$\frac{dx_h}{d\tau} = -\frac{w'(xh)\frac{dt_h}{d\tau}}{C''(x_h) + t_h w''(x_h)}.$$

When $\frac{dt_h}{d\tau} > 0$, which is always true if $t_h < v$, we can show that $\frac{dx_h}{d\tau} < 0$.

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