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Liberalizing trade in environmental goods

By

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Trade liberalization in environmental goods is high on the agenda of the current Doha round. We examine its effects in a model with one domestic downstream polluting firm and two upstream firms (one domestic, one foreign). The domestic government sets the emission tax rate after the outcome of R&D is known. The upstream firms offer their technologies to the downstream firm at a flat fee. The effect of liberalization on the domestic upstream firm's R&D incentive is ambiguous. Liberalization usually results in cleaner production, which allows the country to reach higher welfare. However this increase in welfare is typically achieved at the expense of the environment (a backfire effect). Thus our results cast doubt on the hoped-for "win-win-win" outcome of trade liberalization in environmental goods.

JEL classification: F12, F18, L24, O32, Q55, Q58

Keywords: Pollution abatement technology, R&D, trade and environment, trade liberalization, backfire effect

Outline

Non-Technical Summary

Trade liberalization, brought about by negotiations through the GATT (General Agreement on Tariffs and Trade) and its successor the WTO (World Trade Organization), has greatly expanded international trade and spurred global economic growth over the past 60 years. However, the WTO has come under increased criticism for neglecting the negative side-effects of trade liberalization, especially its potentially detrimental effect on the environment. The WTO must have thought that it could address these criticisms by making trade liberalization in environmental goods and services (EGS) a priority for the Doha round in 2001. The WTO wanted to focus on "those situations in which the elimination or reduction of trade restrictions and distortions would benefit trade, the environment and development". This idea of a "win-win-win" situation is also strongly promoted by the OECD. Surely, trade liberalization in EGS, making cleaner technologies more widely available especially in developing countries, must be good for the environment?

We show that this is not necessarily the case. Trade liberalization does usually lead to cleaner technologies becoming available, which allows a (developing) country to increase its welfare. However, this increase in welfare comes at the expense of the environment. The result is akin to the rebound and backfire effects in energy economics, where an improvement in energy efficiency is partly (rebound effect) or more than completely (backfire effect) offset by an increase in demand for energy. In our case, we could speak of a political backfire effect, because the increase in emissions comes about through an adjustment in environmental policy.

Our analysis is most relevant for developing countries which typically have substantial trade restrictions in EGS. There is a domestic eco-firm that offers a technology that is less clean than the foreign eco-firm's technology. Both firms can do R&D into a new, even cleaner technology. Once the outcome of R&D is known, the domestic government sets the emission tax rate for the polluting industry, which consists of one firm. The eco-firms then try to licence their technologies to this downstream firm. The downstream firm eventually chooses the cleanest technology and produces its consumption good.

We compare autarky, where only the domestic eco-firm can supply the environmental technology, to free trade, where it has to compete with the foreign eco-firm. Trade liberalization usually leads to an increase in welfare because of the availability of cleaner technologies. However, the domestic government takes this opportunity to reduce the effective tax rate on output. The output of the polluting good increases by so much that pollution rises, although the production technology is cleaner.

One might wonder whether the increase in pollution is a cause for worry. After all, environmental quality is only a part of a country's overall welfare. As long as welfare increases, the country is better off, even if the government decides to let pollution rise. However, especially in developing countries, governments might not value the environment enough and the increase in pollution might decrease welfare, especially in the longer run.

Liberalizing Trade in Environmental Goods*

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1 Introduction

While the trade liberalization of the past sixty years has brought great economic growth, recent research suggests it may have harmed the environment.[1] However, surely trade liberalization in environmental goods and services, making cleaner technologies more widely available especially in developing countries, must be good for the environment? This was the thinking at the fourth WTO Ministerial Conference at Doha (WTO, 2001), where "with a view to enhancing the mutual supportiveness of trade and environment", the conference agreed to negotiations on "the reduction or, as appropriate, elimination of tariff and non-tariff barriers to environmental goods and services". It instructed the Committee on Trade and Environment to give particular attention to "those situations in which the elimination or reduction of trade restrictions and distortions would benefit trade, the environment and development". This idea of a "win-win-win" solution is also strongly promoted by the OECD (2003, 2005).

In this paper, we examine the effect of trade liberalization in environmental goods and services (EGS) on a country's eco-industry, its welfare and its environmental quality. Our analysis is especially relevant for developing countries where the demand for EGS is fast expanding while the domestic sector is still immature[2] and tariffs on EGS are relatively high (OECD, 2005).

We will model EGS as cleaner production technologies. We consider a vertical industry model where the downstream good's production is polluting and the upstream industry is engaged in R&D to develop a cleaner technology which it can sell to the downstream firm for a license fee. The upstream firm faces competition with a foreign firm under the free trade regime.

We find that the effect of trade liberalization on the incentive for the domestic

[1] Antweiler et al. (2001) find that trade liberalization has generally reduced SO_2 concentrations. Cole and Elliott (2003) suggest trade liberalization will reduce Biochemical Oxygen Demand, but increase CO_2 and NO_x emissions. Managi et al. (2009), treating trade and income as endogenous, conclude that trade has benefited the environment in OECD countries, but increased SO_2 and CO_2 emissions in non-OECD countries. Kellenberg (2009) finds that a large part of a developing country's success in attracting FDI from the US can be attributed to weakening environmental regulation.

[2] OECD (2005) predicts that the EGS market will grow by less than 1% in developed countries and by 8.6% in the developing countries. In 2003 nearly 80% of the global exports of EGS originated in developed countries (Hamwey, 2005).

firm to do R&D is ambiguous. Trade liberalization usually leads to the availability of cleaner technologies and higher welfare. However, this increase in welfare comes at the expense of the environment. The government responds to the opportunity for cleaner production by allowing more production, to the point where total pollution increases. Borrowing a term from the energy economics literature (Saunders, 2000), the availability of a cleaner technology causes a backfire effect. Thus we cast doubt on the "win-win-win" outcome that the WTO and OECD hope for: there seems to be a "win" for welfare, but not for environmental quality.

The rest of the paper is organized as follows. In Section 2 we review the relevant literature. After describing the model in Section 3, we solve the game by backwards induction. In Section 4 we analyze how the upstream firms set their technology fees under different possible R&D outcomes. In Section 5, we look at government policy under free trade and autarky. Section 6 discusses the R&D decisions of the firms following which we analyze the effect of trade liberalization on the domestic firm's R&D incentive. In Sections 7 and 8, respectively, we compare expected pollution damage and welfare under autarky and free trade. Section 9 concludes.

2 Literature review

The literature on innovation and adoption of new abatement technology, reviewed by Jaffe et al. (2003) and Requate (2005a), has mostly assumed that if a polluting firm wants to install a new abatement technology, it has to pay a certain installation or (possibly) R&D cost itself. Some authors take into account that one firm can license its invention to other firms. In the papers by Milliman and Prince (1989), Biglaiser and Horowitz (1995), Fischer et al. (2003), the innovator is one of the polluting firms. In other papers, which we will discuss here, there are specialized firms (the eco-industry) that licence their innovations to the polluting industry. In all these papers, and in contrast to our paper, the polluting industry is assumed to be perfectly competitive. Finally, we will review the literature on the eco-industry and international trade. We note that there is also a more general literature on how trade liberalization can increase R&D and improve productivity, both theoretically (e.g. Ederington and McCalman, 2008; Spulber, 2010) and empirically (e.g. Alvarez and López, 2005).

Parry (1995, 1998) sets up a model with free entry into the eco-industry. The probability that a given firm will find (and obtain a patent for) the new technology is decreasing in the number of eco-firms. Parry (1995) argues that when the government sets the emission tax rate before the eco-firms' entry decision, the tax rate will usually be below marginal damage. This is to counter monopoly pricing by the innovator, excessive entry into the eco-industry and the excess of innovator revenue over social benefits. Parry (1998) compares emission taxes, tradable emission permits and relative standards, but only at their respective Pigouvian levels.

Laffont and Tirole (1996) argue that the monopolistic innovator will set a licence fee that slightly undercuts the permit price (effectively an emission tax) set by the regulator. If the regulator sets the permit price after the R&D outcome, she will set it equal to zero in order to obtain complete diffusion of the clean technology. As a result, the innovator's license fee income will be zero, so that he will not invest in R&D. Although the timing of our game is similar to Laffont and Tirole's (1996), we do not encounter the problem of incomplete diffusion, because there is only one firm to which the innovators license their technology.

Denicolò (1999) compares emission taxes and tradable emission permits in a model with a single eco-firm that can invest in making its technology cleaner. Denicolò (1999) finds that that taxes and permits are equivalent when they are set after the eco-firm's investment. The instruments are not equivalent when they are set before the eco-firm's investment, however both instruments lead to underinvestment in R&D.

Requate (2005b) compares emission taxes and tradable permits set under different timings in a model where the monopolistic eco-firm can invest to increase its probability of finding the cleaner technology. He finds that for a given timing, emission taxes always outperform permits, with commitment to a tax contingent on R&D success performing the best. The timing in our game corresponds to Requate's (2005b) timing C: after the R&D outcome is observed, but before the eco-firms set their licence fees.

We now turn to the literature on the eco-industry and international trade. The papers we discuss here (unlike those discussed above and our own paper) all model the eco-industry's product as an input into production, in the sense that the more the downstream firm uses of it, the lower its emissions.[3] When there are multiple eco-firms, they are assumed to produce a homogeneous environmental good from the polluting firm's point of view (although production costs could differ between eco-firms). These papers usually do not consider the eco-industry's R&D incentives. Our paper, on the other hand, assumes that the eco-industry provides an abatement technology, which the downstream firm can either use (against a fee) or not use, and we analyze the eco-industry's R&D incentives.

Feess and Muehlheusser (2002) consider an (otherwise symmetric) international Cournot duopoly with an eco-firm in the home country. Unlike in our model, Feess and Muehlheusser (2002) assume that the price of its product is exogenously given. The authors find that if the eco-firm benefits from a higher tax rate, the home goverment will set a higher tax rate than the foreign government. The home government may lower its tax rate when there is learning by doing.

Greaker (2006) shows how a country can increase the export market share of its (perfectly competitive) polluting industry by committing to a low level of allowed emissions per firm. This is because stricter environmental policy leads more firms to pay the initial R&D costs to enter the eco-industry. This increased competition in the eco-industry lowers the price of the environmental good.

Greaker and Rosendahl (2008) employ a two-country model with an eco-firm in each country, supplying the perfectly competitive polluting industries in both countries. The governments move first, setting a maximum emissions-to-output ratio and a subsidy for R&D with which the eco-firm tries to reduce the marginal cost of producing its environmental good. The authors find that a more stringent environmental policy is good for the domestic polluting industry, because it reduces the price of abatement equipment. However, the increase in demand from the domestic polluting industry may benefit the foreign eco-firm at the expense of the domestic eco-firm.

Canton (2007) considers a framework similar to Greaker and Rosendahl's (2008), but with governments committing to an emission tax rate and different assumptions

[3] David and Sinclair-Desgagné (2005) and Canton et al. (2008) also employ this assumption, but do not analyze international trade.

on the ownership of the eco-firms. With Northern shareholders owning an eco-firm in both countries, the Southern government sets its tax rate lower than its Northern counterpart, and lower than marginal damage, to reduce the revenue of the foreign-owned eco-firm. With Southern shareholders owning a rival firm (with higher production costs) in both countries, and with each eco-firm's production increasing in the tax rate, the Southern government sets a lower tax rate than in the cooperative outcome. This is because as an importer of EGS, it is trying to lower its price, and because it is only considering the positive effect of a higher tax rate on Southern-owned eco-firms. For the North, as an exporter of EGS, the comparison of the tax rates is ambiguous.

In a framework similar to Canton (2007) but with a monopolistic Northern eco-firm, Nimubona (2008) shows that an import tariff on EGS helps the Southern government extract rents from the eco-firm. An exogenous decrease in the tariff leads to a lower emission tax in the South if the South cannot fully extract the eco-firm's rents. While EGS imports rise, the decrease in the tax rate results in higher production, so that pollution may actually increase. Like Nimubona (2008), we find that trade liberalization usually increases the expected cleanliness of production, but when it does, it also increases pollution. However, our model is quite different in that we model EGS as a technology, we assume there is a Southern eco-firm, and we model trade liberalization as a discrete jump from autarky to completely free trade rather than a marginal reduction in the tariff.

3 The model

We consider the market for a consumption good, for which domestic demand is given by $P = A - q$, with P the product price, q production and $A > 0$. There is one domestic producer of the good (the downstream firm), with constant marginal cost of production c. We will normalize $A - c = 1$, so that:

$$P - c = 1 - q \tag{1}$$

There is no international trade in this good. Production of the good is polluting.

Environmental damage of emissions E is:

$$D(E) = \frac{1}{2}\lambda E^2 \tag{2}$$

The emissions-to-output ratio e depends on the abatement technology that the downstream firm is using. If it does not use any abatement technology, e is normalized to one. The downstream firm can also use an abatement technology that an upstream firm has developed, for a flat fee F.

The domestic (foreign) upstream firm has an abatement technology available with $e = e_h$ (e_f), with $e_f < e_h < 1$, i.e. the foreign firm's technology is more efficient. Both firms can do R&D into a new technology with $e = e_n$, $e_n < e_f$. For both firms, the cost of R&D is R and the probability of finding the new technology is p. Environmental policy consists of an emission tax. The domestic government sets the tax rate at the level that maximizes domestic welfare.

We compare the regimes of autarky A and free trade T. With autarky, the domestic downstream firm cannot use the technology from the foreign upstream firm; with free trade it can.[4]

The game under autarky A is as follows:

1. The domestic upstream firm decides whether or not to do R&D, and the outcome of R&D is observed.

2. The domestic government sets the emission tax rate.

3. The domestic upstream firm sets the technology fee.

4. The downstream firm decides which abatement technology to use and sets its output level.

The game under free trade T is:

1. The domestic and foreign upstream firms decide whether or not to do R&D, and the outcome of R&D is observed.

[4] We assume the downstream firm cannot make an imperfect imitation of the abatement technologies itself (Parry, 1995, 1998; Spulber, 2010).

2. The domestic government sets the emission tax rate.

3. The domestic and foreign upstream firms set their technology fees.

4. The downstream firm decides which abatement technology to use and sets its output level.

4 License fee and output decisions

In this section, we will solve for stages 3 and 4 of the game, introducing some constraints we will have to impose on the parameters.

Using backwards induction, we start the analysis in stage 4. For stages 2 to 4, there are several scenarios s, to be defined later in this subsection. The downstream firm's profit gross of the license fee in scenario s with technology i is, from (1):

$$\pi_i^s = (1 - q_i^s - te_i)\, q_i^s \tag{3}$$

Differentiating (3) and solving for q_i^s yields:

$$q_i^s = \frac{1 - te_i}{2} \tag{4}$$

Substituting (4) into (3), we get the gross profit of the downstream firm as:

$$\pi_i^s = \left[\frac{1 - te_i}{2}\right]^2 = (q_i^s)^2 \tag{5}$$

Moving on to stage 3, denote the upstream firm with the most (least) efficient technology e_1 (e_2) by firm 1 (2), i.e. $e_1 \leq e_2$. Firms 1 and 2 engage in price competition to sell their technology to the downstream firm. In autarky, the domestic upstream firm is always firm 1 and there is no firm 2.

In equilibrium, firm 1 will charge a fee of

$$F^s = \pi_1^s - \pi_2^s \tag{6}$$

Firm 2 will charge a fee of 0. Strictly speaking, the downstream firm will then be indifferent between the technology offered by firm 1 and the technology offered by firm 2 (with free trade) or no abatement technology (in autarky). We assume that the firm will choose firm 1's technology. This is because firm 1 could always charge slightly less than F^s in (6) to make the downstream firm prefer its technology.

The net profit Π^s of the downstream firm (net of the license fee for the efficient technology) is then:

$$\Pi^s = \pi_1^s - F^s = \pi_2^s \tag{7}$$

In order to avoid complications with corner solutions, we wish to restrict our analysis such that $q_2^s > 0$ for all admissible values of e_i. In subsections 5.1 and 5.2.1, we will see that $q_2^s > 0$ always holds under autarky as well as in free trade scenarios nf and nn for:

$$\lambda < \lambda_0^A \equiv \frac{5}{2}\sqrt{5} + \frac{11}{2} \approx 11.09 \tag{8}$$

In subsection 5.2.2, we will see that $q_2^s > 0$ always holds under free trade scenarios fh and nh for:

$$\lambda < \lambda_0^T \equiv \frac{3\sqrt{5}+5}{2e_h^2} \approx \frac{5.8541}{e_h^2} \tag{9}$$

We will see in Section 5 that the licence fee is first increasing and then decreasing in the quality of the superior technology e_1. From (5) and (6), we can write:

$$\frac{dF^s}{de_1} = -t^s q_1^s + [E_2^s - E_1^s] \frac{dt^s}{de_1} \tag{10}$$

An improvement in the best technology on offer (a decrease in e_1) has two effects on the licence fee. First, for a given tax rate, it increases the profits the downstream firm can obtain and thus raises the fee. This is the first term on the RHS of (10). Secondly, the tax rate changes. The effect on F^s is given by the second term on the RHS of (10), where $E_2^s > E_1^s$. Initially, the tax rate might increase as the technology gets better, as we will see in (15). This would cause a further increase in the fee. However, eventually the tax rate will start to decline, which has a negative effect on the fee. Eventually, the second effect dominates as the tax rate and the fee decline to zero.

We restrict our analysis to a level of abatement technology such that the license fee is decreasing in $e_i : dF^s/de_1 < 0$. If instead $dF^s/de_1 > 0$, the upstream firm would realize that it could gain a higher fee with a worse technology. This would give the firm an incentive to tinker with or sabotage the technology, increasing its e_i and gaining a higher licence fee. Table 1 in Section 5 presents the critical values of e_n and e_h for selected values of λ, above which $dF^s/de_1 < 0$.

Finally, let us define the scenarios. In autarky, the scenarios are $n0$ and $h0$ when the domestic upstream firm has and has not found the new technology, respectively. In both scenarios, the downstream firm chooses to use the domestic upstream firm's technology. With free trade, the scenarios with their equilibrium outcomes are:

- fh : Neither the domestic nor the foreign firm has found the new technology. Then the foreign firm will supply the technology e_f to the downstream firm.
- nh : Only the foreign firm has found the new technology. The foreign firm will supply the technology e_n to the downstream firm.
- nf : Only the domestic firm has found the new technology. The domestic firm will supply the technology e_n to the downstream firm.
- nn : Both firms have found the new technology. They compete the fee down to zero. The domestic firm is indifferent between the two upstream firms' offers.

5 Government Policy

In the second stage of the game, the goverment sets the emission tax rate that maximizes domestic welfare W^s in scenario s, given that the domestic firm uses the most efficient technology e_1. Social welfare is the sum of the domestic upstream and domestic downstream firms' profits, consumer surplus and tax revenues, minus environmental damage (2):

$$W^s = \Pi^s + F_h^s + \frac{1}{2}\left[q_1^s\right]^2 + te_1q_1^s - \frac{1}{2}\lambda\left[e_1q_1^s\right]^2 \tag{11}$$

Two conflicting forces are at work when the government sets the tax rate. On the one hand the government wants to tax pollution, because there is too much of it. This is the overriding concern when e_1 is high, resulting in a positive tax rate. On the other hand, it wants to subsidize the downstream firm's production, because there is too little of it, due to monopoly power. The government cannot subsidize production directly, therefore it lowers the pollution tax instead. Since the emissions-to-output ratio is given, there is only one variable that the government needs to control. Given the technologies that are available, the government can thus reach the first best with the single instrument of the emission tax. When e_1 is low, the government is more worried about underproduction than about pollution, so it sets a negative tax rate. In the following, we will exclude from our analysis values of e_1 so low that t becomes negative. Indeed, as we have announced in Section 4, we will even exclude higher e_1 values for which t is positive, but the licence fee is increasing in e_1.

5.1 Autarky

Denote the domestic upstream firm's technology in stage 3 by $e_i,\ i = h, n$. With $e_1 = e_i,\ \Pi^{i0} + F_h^{i0} = \pi_i^{i0}$ by (7). Substituting this, (4) and (5) into (11), social welfare in scenario $i0$ is given by:

$$W^{i0} = \left[\frac{1 - te_i}{2}\right]^2 + \frac{1}{2}\left[\frac{1 - te_i}{2}\right]^2 + te_i\left(\frac{1 - te_i}{2}\right) - \frac{1}{2}\lambda\left[e_i\left(\frac{1 - te_i}{2}\right)\right]^2 \tag{12}$$

Differentiating and solving for t^{i0} yields:

$$t^{i0} = \frac{\lambda e_i^2 - 1}{e_i\left(1 + \lambda e_i^2\right)} \tag{13}$$

The tax rate is positive if and only if:

$$\lambda e_i^2 > 1 \tag{14}$$

Differentiating the tax rate with respect to e_i, we find:

$$\frac{dt^{i0}}{de_i} = \frac{1 + 4\lambda e_i^2 - \lambda^2 e_i^4}{e_i^2\left(1 + \lambda e_i^2\right)^2} \tag{15}$$

The RHS is negative for high values of λ and e_i, but positive for low enough values of e_i. Thus as abatement technology improves (e_i declines), the tax rate may first increase, but will eventually decrease in the quality of the technology. It is easily seen that the effective tax rate on output $t^{i0}e_i$ is always increasing in e_i.

Substituting (13) into (4) and (5), we find the equilibrium output and profits:

$$q_i^{i0} = \frac{1}{\lambda e_i^2 + 1} \tag{16}$$

$$\pi_i^{i0} = \frac{1}{\left(\lambda e_i^2 + 1\right)^2} \tag{17}$$

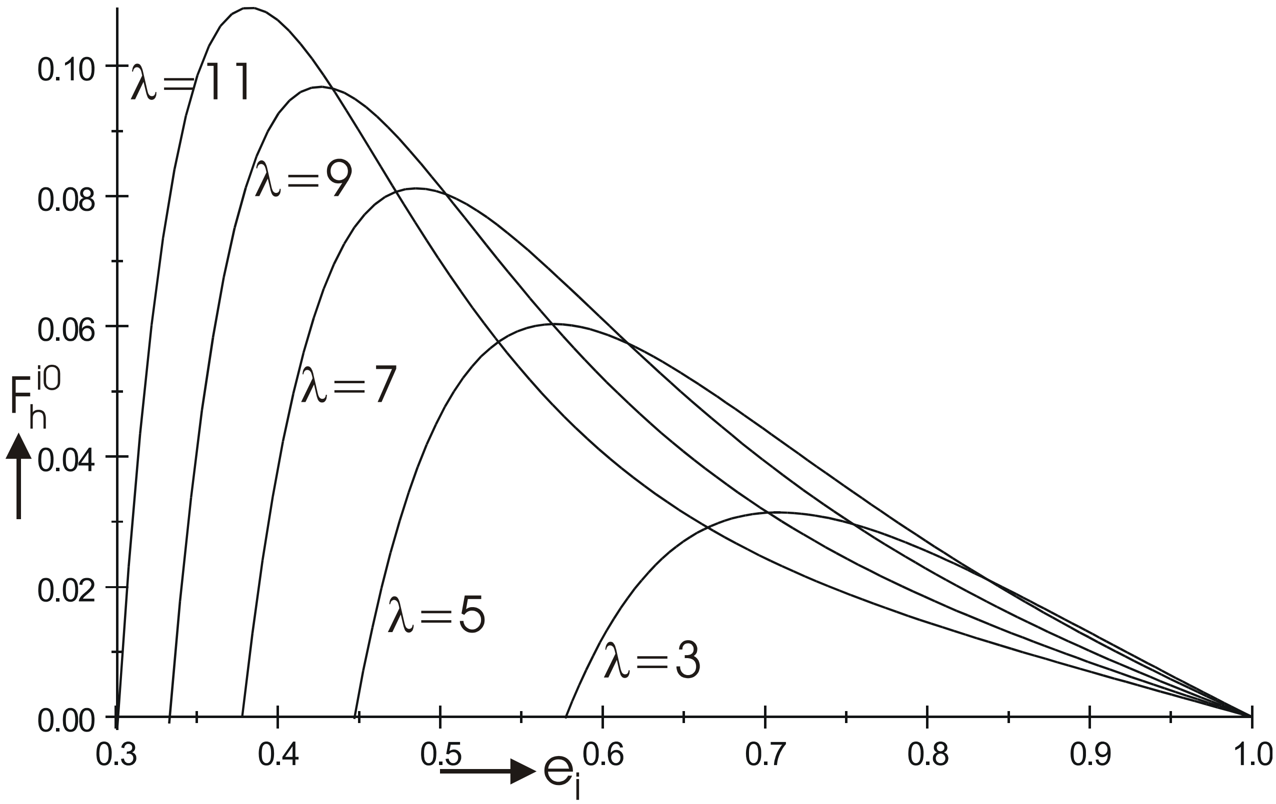

Figure 1: The domestic firm's licence fee F_h^{i0} under autarky when the domestic firm has technology $e_i,\ i = h, n$.

From (16), emissions are:

$$E^{i0} = \frac{e_i}{\lambda e_i^2 + 1} \tag{18}$$

Substituting (13) and (16) into (12) yields welfare under autarky:

$$W^{i0} = \frac{1}{2\left(1 + \lambda e_i^2\right)} \tag{19}$$

Substituting (13) into (4), we see that output without any abatement technology would be:

$$q_0^{i0} = \frac{\lambda e_i^3 - \lambda e_i^2 + e_i + 1}{2e_i\left(\lambda e_i^2 + 1\right)} \tag{20}$$

In order to avoid corner solutions, we would like q_0^{i0} to be positive. In Appendix A.1 we will see that $q_0^{i0} > 0$ for all admissible values of e_i as long as $\lambda < \lambda_0^A$ as defined in (8).

Substituting (20) into (5) and (7), we obtain the downstream firm's net profit (after paying the license fee):

$$\Pi^{i0} = \pi_0^{i0} = \left[\frac{\lambda e_i^3 - \lambda e_i^2 + e_i + 1}{2e_i\left(\lambda e_i^2 + 1\right)}\right]^2 \tag{21}$$

Substituting (17) and (21) into (6), we obtain the technology fee as:

$$F_h^{i0} = \left[\frac{1}{\lambda e_i^2 + 1}\right]^2 - \left[\frac{\lambda e_i^3 - \lambda e_i^2 + e_i + 1}{2e_i\left(\lambda e_i^2 + 1\right)}\right]^2 \tag{22}$$

Figure 1 shows the licence fee F_h^{i0} as a function of e_i for different values of $\lambda < \lambda_0^A$ (where λ_0^A is defined in (8)). As explained in Section 4, while the fee is first increasing and then decreasing in e_i, we will impose $dF_h^{i0}/de_i < 0$. The condition $dF_h^{i0}/de_i < 0$ is binding for $i = n$, because it is clear from Figure 1 that when $dF_h^{n0}/de_n < 0$, then $dF_h^{h0}/de_h < 0$ as well, since $e_h > e_n$.

5.2 Free Trade

5.2.1 Domestic firm has found the new technology

In scenarios $nk,\ k = f, n$, the domestic upstream firm supplies the technology.[5] Substituting $e_1 = e_n,\ e_2 = e_k$ and $\Pi^{nk} + F_h^{nk} = \pi_n^{nk}$ by (7), along with (4) and (5) into (11), social welfare in scenario nk is:

$$W^{nk} = \left[\frac{1 - te_n}{2}\right]^2 + \frac{1}{2}\left[\frac{1 - te_n}{2}\right]^2 + te_n\left(\frac{1 - te_n}{2}\right) - \frac{1}{2}\lambda\left[e_n\left(\frac{1 - te_n}{2}\right)\right]^2 \tag{23}$$

Differentiating and solving for t^{nk} yields:

$$t^{nf} = t^{nn} = \frac{\lambda e_n^2 - 1}{e_n\left(\lambda e_n^2 + 1\right)} \tag{24}$$

Substituting this into (5) and (3), we obtain the equilibrium outputs and profits as:

$$q_n^{nf} = q_n^{nn} = \frac{1}{\lambda e_n^2 + 1} \tag{25}$$

$$\pi_n^{nf} = \pi_n^{nn} = \frac{1}{\left(\lambda e_n^2 + 1\right)^2} \tag{26}$$

From (25), emissions are:

$$E^{nf} = E^{nn} = \frac{e_n}{\lambda e_n^2 + 1} \tag{27}$$

[5] In fact, in scenario nn, the upstream firms compete the fee down to zero and the firm as well as the government are indifferent between the two suppliers. For expositional simplicity, we let the domestic firm supply the technology.

Substituting (24) and (25) into (23), we find that welfare is:

$$W^{nf} = W^{nn} = \frac{1}{2\left(\lambda e_n^2 + 1\right)} \tag{28}$$

For scenario nf, substituting (24) into (4), we find the equilibrium output of the downstream firm when it uses the less efficient technology e_f:

$$q_f^{nf} = \frac{\lambda e_n^3 - e_f \lambda e_n^2 + e_n + e_f}{2e_n\left(\lambda e_n^2 + 1\right)} \tag{29}$$

It is easily seen that by (14), $q_f^{nf} > q_0^{n0}$ in (20). Thus, condition (8) that ensures $q_0^{n0} > 0$ is also sufficient for $q_f^{nf} > 0$.

Substituting (24) into (7) and (3), we obtain the downstream firm's net profit (after paying the technology license fee):

$$\Pi^{nf} = \pi_f^{nf} = \left[\frac{\lambda e_n^3 - e_f \lambda e_n^2 + e_n + e_f}{2e_n\left(\lambda e_n^2 + 1\right)}\right]^2 \tag{30}$$

Substituting (26) and (30) into (6), the domestic upstream firm's licence fee is:

$$F_h^{nf} = \left[\frac{1}{\lambda e_n^2 + 1}\right]^2 - \left[\frac{\lambda e_n^3 - e_f \lambda e_n^2 + e_n + e_f}{2e_n\left(\lambda e_n^2 + 1\right)}\right]^2 \tag{31}$$

For scenario nn, we have $F_h^{nn} = 0$ and $\Pi^{nn} = \pi_n^{nn}$ as given by (26), so that $\Pi^{nn} + F_h^{nn} = \Pi^{nf} + F_h^{nf}$.

For the reasons explained in subsection 4, we would like F_h^{nf} to be decreasing in e_n. Comparing F_h^{nf} in (31) to F_h^{n0} in (22) with $i = n$, we see that the only difference lies in the alternative technology e_2 which is $e_f < 1$ in scenario nf and $e = 1$ in $n0$. At the point where $dF_h^{n0}/de_n = 0$, we must have $dt^{n0}/de_n > 0$ by (10). Then since E_2 is lower in scenario nf than in $n0$, $dF_h^{nf}/de_n < 0$ at the point where $dF_h^{n0}/de_n = 0$ and $dF_h^{nf}/de_n = 0$ occurs at a lower value of e_n than $dF_h^{n0}/de_n = 0$. Thus as long as $dF_h^{n0}/de_n < 0$, then $dF_h^{nf}/de_n < 0$ as well.

5.2.2 Domestic firm has not found the new technology

In scenarios $jh,\ j = f, n$, the foreign firm supplies the technology to the downstream firm. Substituting $e_1 = e_j$, $e_2 = e_h$, $F_h^{jh} = 0$ and $\Pi^{jh} = \pi_h^{jh}$ (by (7)) along with (4) and (5) into (11), social welfare in scenario jh is:

$$W^{jh} = \left[\frac{1 - te_h}{2}\right]^2 + \frac{1}{2}\left[\frac{1 - te_j}{2}\right]^2 + te_j\left(\frac{1 - te_j}{2}\right) - \frac{1}{2}\lambda\left[e_j\left(\frac{1 - te_j}{2}\right)\right]^2 \tag{32}$$

Differentiating and solving for t^{jh} yields:

$$t^{jh} = \frac{\lambda e_j^3 + e_j - 2e_h}{\lambda e_j^4 + 3e_j^2 - 2e_h^2} \tag{33}$$

The denominator on the RHS is positive, because it is the second order condition for welfare maximization. Thus $t^{jh} > 0$ holds in the welfare optimum if and only if:

$$\lambda e_j^3 + e_j - 2e_h > 0 \tag{34}$$

Substituting (33) into (4), we find the output of the downstream firm when using the less efficient technology e_h:

$$q_h^{jh} = \frac{e_j\left(3e_j - e_h + e_j^3\lambda - \lambda e_j^2 e_h\right)}{2\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)} \tag{35}$$

In order to avoid corner solutions, we would like q_h^{jh} to be positive. In Appendix A.2 we will see that $q_h^{jh} > 0$ for all admissible values of e_j as long as $\lambda < \lambda_0^T$ as defined in (9).

Substituting (33) into (4), we obtain the equilibrium output and profit as:

$$q_j^{jh} = \frac{e_j^2 + e_j e_h - e_h^2}{\lambda e_j^4 + 3ej^2 - 2e_h^2} \tag{36}$$

$$\pi_j^{jh} = \left[\frac{e_j^2 + e_j e_h - e_h^2}{\lambda e_j^4 + 3ej^2 - 2e_h^2}\right]^2 \tag{37}$$

Note that $q_j^{jh} > 0$ since $q_j^{jh} > q_h^{jh} > 0$ by (9) and $e_j < e_h$.

From (36), emissions are:

$$E^{jh} = \frac{e_j\left(e_j e_h + e_j^2 - e_h^2\right)}{\lambda e_j^4 + 3e_j^2 - 2e_h^2} \tag{38}$$

Substituting (33) and (36) into (32) we find welfare as:

$$W^{jh} = \frac{\lambda e_j^4 - 2e_h e_j^3\lambda + e_h^2 e_j^2\lambda + 5e_j^2 - 2e_h e_j - e_h^2}{4\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)} \tag{39}$$

Substituting (35) into (5) and (7) yields the dowstream firm's net profit (after paying the license fee) as

$$\Pi^{jh} = \pi_h^{jh} = \left[\frac{e_j\left(3e_j - e_h + e_j^3\lambda - \lambda e_j^2 e_h\right)}{2\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)}\right]^2 \tag{40}$$

Table 1: Critical values for e_h and e_n according to $dF_h^{n0}/de_n = 0$ in (22) and $dF_f^{nh}/de_n = 0$ in (41)

λ	(e_n^*, e_h^*) in $dF_h^{n0}(e_n^*)/de_n = dF_f^{nh}(e_n^*, e_h^*) = 0$	$(\bar{e}_n, e_h^{\max})$ in $dF_f^{nh}(\bar{e}_n, e_h^{\max}) = 0$
3	(0.708; 0.779)	(0.807; 1)
5	(0.570; 0.644)	(0.673; 1)
7	(0.485; 0.551)	(0.565; 0.914)
9	(0.426; 0.483)	(0.498; 0.807)
11	(0.383; 0.432)	(0.451; 0.730)

Substituting (37) and (40) into (6), we find that the technology fee is:

$$F_f^{jh} = \left[\frac{e_j^2 + e_j e_h - e_h^2}{\lambda e_j^4 + 3e_j^2 - 2e_h^2}\right]^2 - \left[\frac{e_j\left(3e_j - e_h + e_j^3\lambda - \lambda e_j^2 e_h\right)}{2\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)}\right]^2 \tag{41}$$

As with F_h^{i0} in Figure 1, the fee is first increasing and then decreasing in the quality of the best (here: the foreign firm's) technology, for reasons explained in Section 4. As also explained in Section 4, we will restrict ourselves to values of e_n for which the fee is decreasing in e_n.

Table 1 shows the critical values of e_h and e_n at which $dF_h^{n0}/de_n = 0$ in (22) and $dF_f^{nh}/de_n = 0$ in (41). For $\lambda = 3$, for instance, $dF_h^{n0}/de_n = 0$ at $e_n = 0.708$ and $dF_f^{nh}/de_n = 0$ at $(e_n, e_h) = (0.708; 0.779)$. Thus for $0.708 < e_h < 0.779$, the binding constraint is $dF_h^{n0}/de_n < 0$, which requires $e_n > 0.708$. For $e_h > 0.779$, the binding constraint is $dF_f^{nh}/de_n < 0$, which implies that the minimum value of e_n is increasing in e_h. For the maximum value of one for e_h, the minimum value of e_n is 0.807. For the λ values of 3 and 5, the maximum value of e_h is one, whereas for higher λ's it is constrained by (9).

6 R&D decisions

In this section we solve for stage one of the game under autarky (subsection 6.1) and free trade (subsection 6.2) and we compare the domestic firm's R&D incentives under both regimes (subsection 6.3).

Table 2: Payoff matrix for the domestic and foreign firms' Research and Development decisions

Home/Foreign	R&D	No R&D
R&D	$p\left(1-p\right)F_h^{nf}-R;\ \left(1-p\right)^2 F_f^{fh}+p\left(1-p\right)F_f^{nh}-R$	$pF_h^{nf}-R;\ \left(1-p\right)F_f^{fh}$
No R&D	$0;\ pF_f^{nh}+\left(1-p\right)F_f^{fh}-R$	$0;\ F_f^{fh}$

Note: F_h^{nf} given by (31); F_f^{fh}, F_f^{nh} given by (41) with $j=f,n$.

6.1 Autarky

In autarky, the domestic firm will undertake R&D if its expected payoff from undertaking R&D exceeds its payoff from not doing R&D:

$$pF_h^{n0}+(1-p)F_h^{h0}-R>F_h^{h0}$$

with F_h^{i0}, $i=n,h$, given by (22). Thus the firm will do R&D if and only if:

$$R<R_h^A\equiv p\left(F_h^{n0}-F_h^{h0}\right) \tag{42}$$

R_h^A is positive by our assumption, introduced in subsection 5.1, that F_h^{i0} is decreasing in e_i, $i=h,n$.

6.2 Free trade

Table 2 shows the payoff matrix for the domestic and foreign upstream firms in stage one, depending on either firm's decision whether or not to do R&D. The first term in each cell shows the payoff to the domestic firm and the second term shows the payoff to the foreign firm.

6.2.1 Comparing the domestic and foreign firm's threshold to do R&D

Let us first look at the foreign firm's incentive to do R&D. In case the domestic firm does R&D, the foreign firm will do R&D when:

$$R<R_f^1\equiv p\left(1-p\right)\left(F_f^{nh}-F_f^{fh}\right) \tag{43}$$

R_f^1 is positive by our assumption, introduced in subsection 5.2.2, that F_f^{jh} is decreasing in e_j, $j=n,f$.

In case the domestic firm does not do R&D, the foreign firm will not do R&D when:

$$R > R_f^2 \equiv p\left(F_f^{nh} - F_f^{fh}\right) \tag{44}$$

Like R_f^1, R_f^2 is positive by our assumption that F_f^{jh} is decreasing in e_j, $j = n, f$.

It is easily seen from (43) and (44) that when the domestic firm does R&D the critical R&D cost level for the foreign firm is lower:

$$R_f^1 < R_f^2 \tag{45}$$

The reason for this is that without domestic R&D, the foreign firm can always increase its fee from F_f^{fh} to F_f^{nh} if it finds the new technology. With domestic R&D, the foreign firm can only make this increase if the domestic firm does not find the new technology. In case the domestic firm finds the new technology, the foreign firm does not earn any fee, whether it is successful itself (then the fee is competed down to zero) or not (then the domestic firm's technology is better).

Now we turn to the domestic upstream firm's incentive to do R&D. If the foreign firm does R&D, the domestic firm will undertake R&D when:

$$R < R_h^1 \equiv p(1-p)\,F_h^{nf} \tag{46}$$

R_h^1 is positive by our assumption, introduced in subsection 5.2.1, that F_h^{nf} is decreasing in $e_n < e_f$.

In case the foreign firm does not do R&D, the domestic firm does not do R&D for:

$$R > R_h^2 \equiv pF_h^{nf} \tag{47}$$

Like R_h^1, R_h^2 is positive by our assumption that F_h^{nf} is decreasing in $e_n < e_f$.

It is easily seen from (46) and (47) that for the domestic firm as well, its critical R&D cost level is lower if the rival firm does R&D:

$$R_h^1 < R_h^2 \tag{48}$$

The reason is analogous to the reason behind inequality (45).

It is unclear in general whether R_h^1 in (46) and R_h^2 in (47) are larger or smaller than R_f^1 in (43) and R_f^2 in (44), respectively. Both comparisons depend on whether F_h^{nf} is larger or smaller than $F_f^{nh} - F_f^{fh}$. However, it can be shown that for most admissible parameter values:

$$F_h^{nf} > F_f^{nh} - F_f^{fh} \tag{49}$$

which is what we shall assume from now on. Combining (49) with (43), (44), (46) and (47) yields:

$$R_f^1 < R_h^1, \qquad\qquad R_f^2 < R_h^2 \tag{50}$$

Thus the domestic firm's R&D incentive is larger than the foreign firm's incentive. One might think that this would always hold, because $F_h^{nf} > F_f^{nh}$ since the domestic government discriminates against the foreign firm. However, since the domestic firm is competing against technology e_f which is better than the technology e_h against which the foreign firm is competing, F_f^{nh} may exceed F_h^{nf}. Not even the fact that the foreign firm will lose $F_f^{fh} > 0$ if it finds the new technology can ensure that (49) always holds.

6.2.2 Equilibria

Combining (50) with (45) and (48) yields:

$$R_f^1 < R_h^1 < R_h^2, \qquad\qquad R_f^1 < R_f^2 < R_h^2 \tag{51}$$

It then follows that there are equilibria (R&D, R&D) when $R < R_f^1$, (R&D, No R&D) when $R_f^1 < R < R_h^2$ and (No R&D, No R&D) when $R > R_h^2$. If $R_h^1 < R_f^2$, then there is an additional equilibrium equilibrium namely (No R&D, R&D) when $R_h^1 < R < R_f^2$. In order to avoid the complication of multiple equilibria, we shall assume that $R_h^1 > R_f^2$. From (46) and (44), this inequality holds if and only if:

$$p < p^* \equiv 1 - \frac{F_f^{nh} - F_f^{fh}}{F_h^{nf}} \tag{52}$$

The RHS of (52) is positive by (49) and less than one because of our assumption, introduced in subsection 5.2.2, that F_f^{jh} is decreasing in e_j, $j = f, n$.

6.3 Domestic firm's R&D incentive

We know from subsection 6.2 that the domestic firm will do R&D in the free trade equilibrium if and only if $R < R_h^2 = pF_h^{nf}$, with F_h^{nf} given by (31). We have to compare this threshold level R_h^2 to the threshold level $R_h^A = p\left(F_h^{n0} - F_h^{h0}\right)$ under autarky from subsection 6.1, with $F_h^{i0}, i = h, n$, given by (22). Free trade gives the domestic firm a larger incentive to invest in R&D if and only if $F_h^{nf} > F_h^{n0} - F_h^{h0}$. There are parameter values of e_n, e_f, e_h and λ such that the domestic firm's R&D incentive is the same under free trade and autarky.

Starting from such a combination of parameter values, the firm will have a higher R&D incentive under trade if e_f increases or if e_h decreases. The former result holds because F_h^{nf} is increasing in e_f by (31): The worse the foreign firm's technology, the higher the license fee the domestic firm can obtain if it finds the new technology and the foreign firm does not, and therefore the higher the domestic firm's R&D incentive under free trade. The latter result holds because F_h^{h0} is decreasing in e_h as discussed in subsection 5.1: The worse the domestic firm's technology, the lower the fee it will obtain for e_h in autarky and therefore the higher the R&D incentive under autarky. Thus the domestic firm will have a higher R&D incentive under free trade than under autarky if e_f is high and e_h is low.

In fact, R_h^A can also be above or below R_f^1, so that any combination of the two possible outcomes under autarky and the three outcomes under free trade can arise.

7 Pollution

7.1 No R&D in autarky; (No R&D, No R&D) with trade

In autarky, emissions are E^{h0} from (18) with $i = h$. With trade, emissions are E^{fh} from (38) with $j = f$. In Appendix A.3 we show that $E^{jh} > E^{h0}$ for the more general case where the foreign firm supplies the technology $e_j, j = f, n$. Thus, emissions are higher with trade than under autarky.

7.2 No R&D in autarky; (R&D, No R&D) with trade

In autarky, emissions are E^{h0} from (18) with $i = h$. With trade, emissions are E^{nf} from (27) if the domestic firm's R&D is successful and E^{fh} from (38) with $j = f$ if it is not. We know from Appendix A.3 that $E^{fh} > E^{h0}$. For the comparision of E^{nf} with

E^{h0}, note that $E^{nf} = E^{n0}$ and $E^{n0} > E^{h0}$ because from (18) for $i = h, n$:

$$\frac{dE^{i0}}{de_i} = \frac{1 - \lambda e_i^2}{\left(\lambda e_i^2 + 1\right)^2} < 0$$

The inequality follows from (14). Thus, in this case as well, expected pollution damage under free trade is greater than under autarky.

7.3 No R&D in autarky; (R&D, R&D) with trade

In autarky, emissions are E^{h0} from (18) with $i = h$. With trade, emissions are $E^{nn} = E^{nf}$ from (27) if R&D by the domestic firm is successful and $E^{jh}, j = f, n$, from (38) if it is not. We know from subsection 7.2 that $E^{nn} = E^{nf} > E^{h0}$ and from Appendix A.3 that $E^{jh} > E^{h0}$ with $j = f, n$. Therefore we can conclude that expected pollution damage under free trade is always greater than the damage under autarky.

7.4 R&D in autarky; (No R&D, No R&D) with trade

In autarky, emissions are E^{n0} if R&D is successful and E^{h0} if it is not. E^{i0} for $i = h, n$ is given by (18). With trade, emissions are E^{fh} from (38) with $j = f$. Thus:[6]

$$D^{NN} - D^{R} = \frac{1}{2}\lambda(E^{fh})^2 - \frac{1}{2}\lambda\left[p\left(E^{n0}\right)^2 + (1-p)\left(E^{h0}\right)^2\right]$$

Solving for p, we see that the pollution damage under free trade is greater than under autarky for:[7]

$$p < p_E \equiv \frac{(E^{fh})^2 - \left(E^{h0}\right)^2}{\left(E^{n0}\right)^2 - \left(E^{h0}\right)^2}$$

When p_E exceeds the maximum value of p^* from (52), environmental damage under free trade will be greater than under autarky. When $p_E < p^*$, damage will be greater under free trade when $p < p_E$ and greater under autarky when $p_E < p < p^*$. However the latter case occurs for a very limited range of parameters only. For most parameter values within the feasible range, expected pollution damage is higher under free trade than under autarky.

[6] D^{XY} and D^X denote expected damage under trade and autarky, respectively, with X (Y) the R&D choice of the domestic (foreign) firm. $X, Y = R, N$ where R (N) means (no) R&D. The same notation is used for W in Section 8.

[7] The numerator on the RHS is positive, as we know from Appendix A.3. The denominator is positive, because $E^{n0} > E^{h0}$ as we have seen in subsection 7.2.

7.5 R&D in autarky; (R&D, No R&D) with trade

In autarky, emissions are E^{n0} if R&D is successful and E^{h0} if it is not. E^{i0} for $i = h, n$ is given by (18). With trade, emissions are E^{nf} from (27) if the domestic firm's R&D is successful and E^{fh} from (38) with $j = f$ if it is not. Since $E^{n0} = E^{nf}$, we have:

$$D^{RN} - D^{R} = \frac{1}{2}\lambda (1 - p) \left[\left(E^{fh}\right)^2 - \left(E^{h0}\right)^2 \right]$$

We have already shown in subsection 7.1 that $E^{fh} > E^{h0}$. Thus we find, again, that pollution is higher under free trade than in autarky.

7.6 R&D in autarky; (R&D, R&D) with trade

In autarky, emissions are E^{n0} if R&D is successful and E^{h0} if it is not. E^{i0} for $i = h, n$ is given by (18). With trade, emissions are $E^{nn} = E^{nf} = E^{n0}$ from (27) if R&D by the domestic firm is successful and $E^{jh}, j = f, n$, from (38) if it is not. Thus we have:

$$D^{RR} - D^{R} =$$

$$\frac{1}{2}\lambda \left[p^2 \left(E^{nn}\right)^2 + p(1-p)\left(E^{nf}\right)^2 + p(1-p)\left(E^{nh}\right)^2 + (1-p)^2\left(E^{fh}\right)^2 - p\left(E^{n0}\right)^2 - (1-p)\left(E^{h0}\right)^2 \right]$$

$$= \frac{1}{2}\lambda(1-p)\left[p\left(E^{nh}\right)^2 + (1-p)\left(E^{fh}\right)^2 - \left(E^{h0}\right)^2 \right]$$

In subsection 7.1 we have seen that $E^{jh} > E^{h0}$ for $j = f, n$. Thus, $D^{RR} - D^{R} > 0$: Expected pollution damage is larger with trade than in autarky.

7.7 Discussion

We can conclude that for all Nash equilibria except [R&D in autarky; (No R&D, No R&D) with trade], expected pollution damage is unambiguously greater under free trade. Paradoxically, these are also the equilibria where trade liberalization leads to a cleaner technology becoming available to the downstream firm. However, the government takes this opportunity for cleaner production to increase welfare (as we will see in the next section) at the expense of the environment. It reduces the effective tax rate te_1 on output, prompting the firm to produce more and ultimately even to pollute more.

The result is similar to the rebound (Khazzoom, 1980) and backfire effects (Saunders, 2000) in energy economics, where the introduction of a more energy-efficient technology (e.g. a more economical car engine) leads to an increase in demand which partly (rebound) or more than completely (backfire) offsets the potential energy saving. Empirically, the rebound effect is generally between 5 and 50% (Binswanger, 2001), but Hanley et al. (2009) find that an energy efficiency improvement in Scotland ultimately backfires. In the same vein, Fisher-Vanden and Ho (2010) predict that a takeoff of the science and technology sector in China will result in cleaner technologies becoming available, but it will increase energy use and CO_2 emissions because of an increase in overall production and a shift to more energy-intensive sectors. Our model could be said to demonstrate a political backfire effect, because the availability of a cleaner technology triggers a change in environmental policy, ultimately resulting in more pollution.

8 Welfare

8.1 No R&D in autarky; (No R&D, No R&D) with trade

For future reference, it will be useful here to consider the more general case where under free trade the foreign firm supplies the technology e_j, where $j = f, n$.

Comparing welfare under autarky (19) with $i = h$ and under free trade (39), it is clear that $W^{h0} = W^{jh}$ for $e_j = e_h$. From (39) we find:

$$\frac{dW^{jh}}{de_j} = \frac{-7e_j e_h^2 + 2e_j^3 + 3e_j^2 e_h - 2\lambda e_j^5 - 2\lambda e_j e_h^4 + 6\lambda e_j^2 e_h^3 - 2\lambda e_j^3 e_h^2 + \lambda^2 e_j^6 e_h - \lambda^2 e_j^5 e_h^2}{2\left(3e_j^2 - 2e_h^2 + \lambda e_j^4\right)^2} \tag{53}$$

In Appendix A.4 we show that $dW^{jh}/de_j < 0$ for $e_j \leq e_h$: The better the technology that the foreign firm supplies, the higher domestic welfare. It follows that welfare under free trade is greater than under autarky.

8.2 No R&D in autarky; (R&D, No R&D) with trade

In autarky, welfare is W^{h0} from (19) with $i = h$. With trade, welfare is $W^{nf} - R$ from (23) if the domestic firm's R&D is successful and $W^{fh} - R$ from (32) with $j = f$ if it is not. Therefore:

$$W^{RN}-W^{N}=pW^{nf}+(1-p)W^{fh}-R-W^{h0}>p\left(W^{nf}-F_{h}^{nf}-W^{h0}\right)+(1-p)\left(W^{fh}-W^{h0}\right)>0$$

The first inequality follows from $R < R_h^2$ in (47). The second inequality follows from the fact that $W^{nf} - F_h^{nf} - W^{h0} > 0$ as shown in Appendix A.5 and $W^{fh} > W^{h0}$ as shown in subsection 8.1. Thus we see that the welfare under free trade is greater than under autarky.

8.3 No R&D in autarky; (R&D, R&D) with trade

In autarky, welfare is W^{h0} from (19) with $i = h$. With trade, welfare is $W^{nf} = W^{nn}$ from (23) if the domestic firm's R&D is successful and $W^{jh}, j = f, n$, from (32) if it is not. Thus we have:

$$W^{RR}-W^{N}=pW^{nf}+(1-p)\,W^{jh}-W^{h0}-R>p\left(W^{nf}-F_{h}^{nf}-W^{h0}\right)+(1-p)\left[W^{jh}-W^{h0}\right]>0$$

The first inequality follows from $R < R_f^1 < R_h^2$ by (51), with R_h^2 given by (47). The second inequality follows from the fact that $W^{nf} - F_h^{nf} - W^{h0} > 0$ as shown in Appendix A.5 and $W^{jh} > W^{h0}$, $j = f, n$, as shown in subsection 8.1. Thus we see that the welfare under free trade is greater than under autarky.

8.4 R&D in autarky; (No R&D, No R&D) with trade

In autarky, welfare is $W^{n0} - R$ if R&D by the domestic firm is successful and $W^{h0} - R$ if it is not. W^{i0} for $i = h, n$ is given by (19). With trade, welfare is W^{fh} from (39) with $j = f$. Thus:

$$W^{NN} - W^{R} = W^{fh} - pW^{n0} - (1-p)\,W^{h0} + R$$

Solving for p, we see that for welfare under free trade to be higher than under autarky:

$$p < p^{w} \equiv \frac{W^{fh} - W^{h0} + R}{W^{n0} - W^{h0}} \tag{54}$$

When p^w exceeds the maximum value of p^* from (52), the expected welfare under free trade will be greater than under autarky. When $p^w < p^*$, expected welfare will be greater under free trade when $p < p^w$ and greater under autarky when $p^w < p < p^*$. It can be shown that p^w can be positive for the lowest possible value of R (R_h^2 from (47)) and it can be below p^* for the highest possible value of R (R_h^A from (42)).

Thus we see that in this equilibrium, welfare could be higher under free trade or under autarky.

8.5 R&D in autarky; (R&D, No R&D) with trade

In autarky, welfare is $W^{n0} - R$ if R&D by the domestic firm is successful and $W^{h0} - R$ if it is not. W^{i0} for $i = h, n$ is given by (19). With trade, welfare is $W^{nf} - R$ from (23) if the domestic firm's R&D is successful and $W^{fh} - R$ from (32) with $j = f$ if it is not. Thus:

$$W^{RN} - W^{R} = pW^{nf} + (1-p)\,W^{fh} - \left[pW^{n0} + (1-p)\,W^{h0}\right] = (1-p)\left[W^{fh} - W^{h0}\right]$$

The second equality follows from $W^{n0} = W^{nf}$. We know from subsection 8.1 that $W^{fh} > W^{h0}$. Thus we conclude that expected welfare is higher under free trade than under autarky.

8.6 R&D in autarky; (R&D, R&D) with trade

In autarky, welfare is $W^{n0} - R$ if R&D by the domestic firm is successful and $W^{h0} - R$ if it is not. W^{i0} for $i = h, n$ is given by (19). With trade, welfare is $W^{nf} = W^{nn} = W^{n0}$ from (23) if the domestic firm's R&D is successful and $W^{jh}, j = f, n$, from (32) if it is not. Thus we have:

$$W^{RR} - W^{R} = (1-p)\left[W^{jh} - W^{h0}\right]$$

In subsection 8.1, we have seen that $W^{jh} > W^{h0}$. Thus $W^{RR} - W^{R} > 0$: Expected welfare under free trade is greater than autarky.

8.7 Discussion

We can conclude that the domestic country is better off with trade liberalization in all the possible Nash equilibria but for [R&D in autarky; (No R&D, No R&D) with trade]. This is because, with free trade, the chance of having a cleaner technology for the downstream firm is higher. In the case of [R&D in autarky; (No R&D, No R&D) with trade], welfare could be higher or lower depending on the probability of success for the domestic firm in finding the new technology. If the probability is very high (low), then under autarky, the welfare is higher (lower) than free trade.

Note finally that the only case in which welfare could be lower with free trade is also the only case in which pollution could be lower with free trade.

9 Conclusion

In this paper we have analyzed the effects of trade liberalization in environmental goods and services (EGS) on a country's domestic eco-firm, on pollution and on welfare.

The effect of trade liberalization on the domestic eco-firm's R&D incentive is ambiguous. The R&D incentive increases with trade if the domestic firm's existing technology is relatively clean (so that its R&D incentive under autarky is low) and the foreign eco-firm's existing technology is not too clean (so that the domestic firm's R&D incentive with trade is high). If the domestic firm does R&D under autarky, but neither firm undertakes R&D with trade, liberalization may decrease welfare. Thus it may be best for a developing country to first liberalize trade in environmental goods with similar countries whose environmental technologies are not too much better than its own. This will stimulate R&D by its domestic eco-industry, increasing welfare and putting the eco-firm in a better position to face competition from more advanced eco-firms at a later date.

Although trade liberalization means that cleaner technologies become available, it generally leads to an increase in pollution. This is because the government takes the opportunity to increase welfare by reducing the effective tax on polluting output, boosting the downstream firm's profits and consumer surplus while increasing pollution. While the WTO argues that trade liberalization in environmental goods and services will benefit the environment as well as the consumer, our model sees the consumer benefit at the expense of the environment. This casts doubt on one of the main motivations for trade liberalization in EGS.

If the eco-industry would invent a technology that was much cleaner than the existing technologies, pollution would decline. However, the eco-industry does not have any incentive to undertake R&D into a very clean technology, or even to market it if it is available. This is because when a very clean technology is available, pollution is not a pressing problem anymore and the government will set a negative environmental tax rate to stimulate production. Thus the eco-industry would not be able to make any money from its invention.

The problem of negative tax rates is particularly severe in our model, because there is just one polluting firm which would like to produce much less than the welfare-maximizing amount. If the industry were more competitive, there would be less need for negative taxes and more incentive for R&D into cleaner technologies. However, for very clean technologies, the tax rate and the license fee would still be decreasing in the cleanliness of the technology, discouraging the eco-industry from R&D into such technologies.

We have seen that welfare usually increases with trade liberalization and generally changes in the same direction as pollution. If trade liberalization increases pollution as well as welfare, one might argue that the increase in pollution is nothing to worry about, because environmental damage is just an element of social welfare, which is increasing overall. However, particularly in developing countries, governments might not value the environment enough and the increase in pollution might reduce welfare, especially in the longer run.

A Appendix

A.1 Condition for $q_0^{i0} > 0$

q_0^{i0} in (20) is decreasing in λ and has an interior minimum in $e_i \in \left[1/\sqrt{\lambda}; 1\right]$ given λ. To make sure that $q_0^{i0} > 0$ for all $e_i \in \left[1/\sqrt{\lambda}; 1\right]$, we calculate the λ where the minimum equals zero. Setting $q_0^{i0} = 0$ and $dq_0^{i0}/de_i = 0$ in (20) yields, respectively:

$$\begin{aligned} \frac{\lambda e_i^3 - \lambda e_i^2 + e_i + 1}{e_i(\lambda e_i^2 + 1)} &= 0 \\ -\lambda^2 e_i^4 + 4\lambda e_i^2 + 1 &= 0 \end{aligned}$$

The only positive solution for λ and e_i is $\lambda = \frac{5}{2}\sqrt{5} + \frac{11}{2}$. Therefore $q_0^{i0} > 0$ for all $e_i \in \left[1/\sqrt{\lambda}; 1\right]$ if and only if inequality (8) holds.

A.2 Condition for $q_h^{jh} > 0$

q_h^{jh} in (20) is positive for all values of e_j for which the second order condition holds (which implies that the denominator on the RHS of (20) is positive) if and only if

$$\lim_{e_j \downarrow \hat{e}_j} \frac{e_j \left(3e_j - e_h + e_j^3\lambda - \lambda e_j^2 e_h\right)}{2\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)} = +\infty \tag{55}$$

where $\hat{e}_j$ as a function of e_h and λ is implicitly defined by:

$$\lambda e_j^4 + 3e_j^2 - 2e_h^2 = 0 \tag{56}$$

The point where the RHS of (55) switches from $+\infty$ to $-\infty$ is where

$$3e_j - e_h + e_j^3\lambda - \lambda e_j^2 e_h = 0 \tag{57}$$

and (56) holds. Solving (56) and (57) simultaneously for λ and e_j, we find that the only positive real solution features is $\lambda = \frac{1}{2(e_h)^2}\left(3\sqrt{5} + 5\right)$. Then $q_h^{jh} > 0$ for all e_j if and only if inequality (9) holds.

A.3 $E^{jh} > E^{h0}$

Comparing emissions under autarky (18) to those under free trade (38), it is clear that $E^{jh} = E^{h0}$ for $e_j = e_h$. From (38) we find:

$$\frac{dE^{jh}}{de_j} = \frac{-\lambda e_j^6 - 2\lambda e_j^5 e_h + 3\lambda e_j^4 e_h^2 + 3e_j^4 - 3e_j^2 e_h^2 - 4e_j e_h^3 + 2e_h^4}{\left(\lambda e_j^4 + 3e_j^2 - 2e_h^2\right)^2}$$

Setting $e_j = e_h$ yields:

$$\left.\frac{dE^{jh}}{de_j}\right|_{e_j=e_h} = \frac{-2e_h^4}{\left(\lambda e_h^4 + e_h^2\right)^2} < 0$$

Thus, when reducing e_j below e_h, E^{jh} initially rises above E^{h0}. However, for lower values of e_j, E^{jh} may decline again. Defining $a \equiv e_j/e_h,\ b \equiv \lambda e_h^2$, we can write

$$E^{jh} = \frac{e_j(a^2+a-1)}{ba^4+3a^2-2}$$

so that

$$E^{jh} - E^{h0} = e_h\left[\frac{(a^3+a^2-a)}{ba^4+3a^2-2} - \frac{1}{b+1}\right] = \frac{e_h\left(a^2-1\right)\left(a-a^2b+ab-2\right)}{(b+1)\left(ba^4+3a^2-2\right)}$$

The (potentially) positive solutions for $E^{jh} = E^{h0}$ are $e_j = e_h$ and

$$a = \frac{1+b\pm\sqrt{b^2-6b+1}}{2} \tag{58}$$

There are only real solutions for a when $b^2-6b+1 \geq 0$, which is satisfied for $b \leq 3-2\sqrt{2}$ and $b \geq 3+2\sqrt{2}$. The first inequality is irrelevant by (14). In case the second inequality holds, the highest possible value for a is for the maximum value of b given by (9), combined with the "+" sign on the RHS of (58), so that:

$$a = \frac{1}{2\left(\frac{3}{2}\sqrt{5}+\frac{5}{2}\right)}\left(\sqrt{\left(\frac{3}{2}\sqrt{5}+\frac{5}{2}\right)^2 - 9\sqrt{5} - 14} + \frac{3}{2}\sqrt{5} + \frac{7}{2}\right) \approx 0.61834 \tag{59}$$

Note that (34) can be written as $ba^3+a-2>0$. Substituting a from (59) and $b = \frac{5}{2}+\frac{3}{2}\sqrt{5}$ from (9), we find $ba^3+a-2=0$, so that (34) is violated. Thus $E^{jh} = E^{h0}$ cannot hold and pollution is higher with trade than under autarky.

A.4 $dW^{jh}/de_j < 0$

The sign of dW^{jh}/de_j in (53) is the sign of the numerator on the RHS. Defining $a \equiv e_j/e_h,\ b \equiv \lambda e_j^2$, the sign of the numerator is the sign of:

$$\Phi = -7a^2 + 2a^4 + 3a^3 - 2ba^4 - 2b + 6ba - 2ba^2 + b^2a^3 - b^2a^2 \tag{60}$$

Φ has a maximum in b for:

$$b = b^* \equiv \frac{3a-a^3-a^2-1}{a^2(1-a)} \tag{61}$$

b^* is positive for $a \in (\bar{a}; 1]$, with $\bar{a} \approx 0.414$. For $a \in [0; \bar{a}]$, Φ reaches its maximum at $b = 0$, which from (60) is clearly negative.

Substituting $b = b^*$ from (61) into (60), we find the maximum possible value of Φ given $a \in (0.414; 1]$:

$$\Phi^* = \frac{1 - 4a^4 + 6a^2 - 5a}{a^2}$$

Plotting this expression shows that $\Phi^* < 0$ for all $a \in (0.414; 1]$. Thus $\Phi < 0$ in (60) for all feasible values of a and b, which means that $dW^{jh}/de_j < 0$ in (53).

A.5 $W^{nf} - F_h^{nf} - W^{h0} > 0$

From (28) and (31):

$$W^{nf} - F_h^{nf} = \frac{1}{2}\frac{\lambda e_n^2 - 1}{(\lambda e_n^2 + 1)^2} + \frac{(\lambda e_n^3 - \lambda e_f e_n^2 + e_n + e_f)^2}{4e_n^2 (\lambda e_n^2 + 1)^2} \tag{62}$$

Differentiating (62) with respect to e_n, we obtain:

$$\frac{d\left(W^{nf} - F_h^{nf}\right)}{de_n} = \frac{\Omega}{2e_n^3 (\lambda e_n^2 + 1)^3} \tag{63}$$

with

$$\Omega \equiv 2a^2 b (3 - b) + a (b + 1) \left(b^2 - 4b - 1\right) - (b - 1) \left(b^2 - 4b - 1\right) \tag{64}$$

where $a \equiv e_n/e_f,\ b \equiv \lambda e_n^2$. Note that $b < \frac{5}{2} + \frac{3}{2}\sqrt{5}$ by (9).

The sign of the RHS of (63) is the sign of Ω which is quadratic in a with a maximum (minimum) for $b > (<)3$. The highest value of Ω is then at $d\Omega/dx = 0$ for $b > 3$ (if this is an internal maximum) and at either the highest or lowest value of a for $b \leq 3$. The highest value of a is 1, for which $\Omega = -2(b + 1) < 0$. The lowest value for a is where $dF_h^{nf}/\partial e_n = 0$ from (31). Substituting this into (64), we find $\Omega = -2a^2 b (b + 1) < 0$. For $b > 3$, the maximum value of Ω in (64) occurs at:

$$a = a^* \equiv \frac{(b + 1) (b^2 - 4b - 1)}{4b(b - 3)}$$

Substituting this into (64), the highest possible value of Ω is:

$$\Omega^* = \left(b^2 - 4b - 1\right) \left(b^4 - 10b^3 + 24b^2 - 30b - 1\right)$$

We see that $a^* > 0$ and $\Omega^* < 0$ for $b \in \left(3; 2+\sqrt{5}\right)$ and $a^* < 0$ and $\Omega^* > 0$ for $b \in \left(2+\sqrt{5}; \frac{5}{2}+\frac{3}{2}\sqrt{5}\right)$. Thus, for all values of b for which there is potentially an interior maximum ($a^* > 0$), Ω^* is negative. We conclude that Ω is negative so that the RHS of (63) is negative. The lowest possible value of $(W^{nf} - F_h^{nf})$ is thus achieved at the maximum value of e_n, which is e_f. Setting $e_n = e_f$ in (62), we obtain from (19):

$$W^{nf} - F_h^{nf} \geq \frac{1}{2\left(\lambda e_f^2 + 1\right)} > \frac{1}{2\left(\lambda e_h^2 + 1\right)} = W^{h0}$$

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