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Summary

This paper considers the question under what conditions domestic markets of emission permits would and should merge to become an international market. Emission permits are licenses, and so governments would need to recognize other countries' permits. In a two-county model, we find that it is in both countries' interests to form an international market, and it may even be beneficial to the environment. Three different policy instruments of the importing country are examined, namely a price instrument (tariff) and two quantity instruments (discount and import quota). All instruments restrict trade. The importing country (and regulator) prefers an import tariff and an import quota to a carbon discount. If the exporting country releases additional permits, the importing country should not try to keep total emissions constant, as that would be ineffective if not counterproductive. Instead, the importing country should aim to keep the total import constant; this would impose costs on the exporting country that are independent of the policy instrument; an import quota would be the cheapest option for the importing country. Compliance and liability issues constrain the market further. However, both the importing and the exporting country would prefer that the permit seller is liable in case of non-compliance, as sellers' liability would less constrain the market.

Keywords: Climate change, emissions trading, environmental policy, liability and compliance

JEL: Q25, Q28

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ON NATIONAL AND INTERNATIONAL TRADE IN GREENHOUSE GAS EMISSION PERMITS

Katrin Rehdanz and Richard S.J. Tol

1. Introduction

The current international climate policy regime, defined by the United Nations Framework Convention on Climate Change (FCCC) and its Kyoto Protocol (KP), is based on binding emission reduction targets and international flexibility mechanisms. However, progress in international negotiations is exceedingly slow, and failure is not excluded. This is not the result from climate change not being a serious problem, or not being recognized as such. The Third Assessment Report of the Intergovernmental Panel on Climate Change confirmed that climate change is for real and its consequences would be better avoided. The slow progress of international negotiations can be explained by the fact that these are negotiations between almost all countries in the world on emission reduction targets for a global externality. Game theory and history suggest that an agreement is improbable (Carraro, 2000; Missfeldt, 1999). It is therefore likely that the Kyoto regime would gradually transform into something different. Some countries may not be prepared to wait for this, though, and implement domestic policies.[1] This paper looks at the issue of coordination of domestic markets of tradable emission permits.[2]

A fundamental problem with the FCCC is that it aims at targets bound by international law.[3] This sounds firm and pro-environmental, but emission reduction would cost money, and it is uncertain how much. Since the economic costs of emission reduction are more imminent than the environmental benefits, the costs of emission abatement dominate the discussion. When sovereign countries negotiate a binding target, they are better off not to reveal their true

[1] Like Denmark and the UK. Both implemented a national emissions trading system recently. For an overview of the development of some national regimes see Ellerman (2000) and RECIEL (2000): Review of European Community & International Environmental Law, Vol. 9, Issue 3. In December 2001, the European Commission (2001) proposed a directive on emissions trading for the European Union and its member states.

[2] Farrell (2001) shows that one key element for a successful emissions trading system is the belief of all participants that climate change is a serious problem and emission control is needed. The second necessary condition is the understanding of the formal structure of how the system should work. However, there is evidence that this might take some time.

[3] As an alternative to the "cap and trade" approach of Kyoto, Bradford (2001) proposes a "no cap but trade" system.

preferences. Instead, they aim for a more conservative outcome, just in case emission reduction turns out to be more expensive than expected.

This is not what came out of the Kyoto negotiations. At first sight, the Kyoto targets are quite ambitious. However, the enforcement mechanisms are weak, and definitions are ambiguous, particularly with regard to carbon sinks. In fact, the Kyoto targets are weak.

Still, the KP has not been ratified, and may never be.[4] We highlight two reasons. First, some countries do not like to be told what to do by international law or the United Nations. Second, some international negotiators may have tried to force their domestic position through international law, as is routinely done in the European Union. For instance, environment representatives dominate some countries' negotiating teams. A strong international treaty would enhance their minority position at home. On the other hand, while preparing for Kyoto, some anti-environment forces may even have pushed for ambitious emission reduction targets, counting on other countries and the ratification process to block emission reduction.

These two reasons stand in the way of not only the KP, but of any treaty that contains internationally legally binding targets. A third obstacle is that international treaties have a different standing in different national law systems, and legal environmental targets mean different things to different governments.

For those reasons, it would be better to have domestic targets for emission reduction, rather than internationally agreed, codified and enforced targets. With domestic emission reduction targets, we mean targets that reflect the balance of domestic opinions about the seriousness of climate change and the costs of emission reduction, targets decisions about which are made through the procedures for decision making common in the country, and targets that are codified and enforced following the usual domestic procedures. Furthermore, domestic targets can be agreed on more efficiently and effectively than international targets that determine domestic policy targets. Domestic targets are also a better reflection of a country's preferences.

[4] Even the EU may not ratify (EUObserver.com, "Denmark likely to block Kyoto ratification", February 19, 2002). Besides, many issues, including ones relating to an international emissions trading system, have been left unresolved. Apart from aspects of allocating emissions permits, accounting principles and market access issues, the implementation of a strong compliance system is a crucial matter. We discuss this in detail in Section 4.

Of course, some form of coordination is necessary. Some countries need to be prodded into action, and naming and shaming may deter potential free-riders. International civil society already plays this role. International networks connect environmental NGOs, if not multinationals themselves; these networks serve to exchange information, coordinate action and exert cross-border pressure. Similarly, businesses with environmental interests have discussion fora and so on.

Coordination is also necessary to minimize the costs of emission reduction.[5] Unilateral emission reduction is much more expensive than multilateral emission abatement, because unilateral emission reduction implies a loss of competitive advantage. So, before targeting its chemical industry, say, a government should be confident that other countries are also regulating its chemical industries to reduce emissions. Therefore, there needs to be an international mechanism through which countries can gain knowledge of and confidence in other countries' emission reduction plans. This coordination needs not be global, however. Only the major trading and investment partners need to be involved. But, coordination can go further.

A domestic market in emission permits is one way to reduce the pain to sectors. If emission reduction is expensive in one sector, it can purchase additional permits from a sector with relatively low reduction costs. The government can further ease the pain through the initial allocation of permits (if "grandfathered") or through the distribution of the revenues (if permits are auctioned). If emission permits were commodities, these domestic markets could easily transform into international markets. Schmidt (2000) shows that, if emission reduction targets are determined by countries in a non-cooperative way, and if emission reduction is achieved in an international market for emission permits, the chosen emission reduction lies very close to the optimal emission reduction under full international cooperation.

Emission permits, however, are not commodities. Emission permits are licenses, and so governments should explicitly recognize other countries' permits. This paper analyses the conditions under which governments would be prepared to do so, and investigates the possibilities of regulating the international market with price and quantity instruments. There

[5] The advantage of coordination with respect to international emission permit trading is its ability to assure least-cost compliance with the particular environmental goal by equalizing marginal costs among all sources. The marginal costs of the selling countries rise and the marginal costs of the buying countries fall, while all gain from trade.

is little, if any literature on this subject. Boom (2001) examines the effects on abatement commitments, total emissions and welfare of international emissions trading. Bohm (1992) and Helm (2000) also investigate the (re)distribution effects of trade. However, these papers do not consider domestic regulation of the international market.

Section 2 starts with a stylized model of two domestic emissions markets. Section 3 extends the model to include regulation by the importing country. Section 4 investigates whether the importing country can prevent the exporting country from issuing additional permits. Section 5 reviews the literature on buyers' and sellers' liability, and examines the consequences for a bi-national market in emission permits. Section 6 presents selected extensions of the model and Section 7 concludes.

2. The case of two domestic emissions markets

Let us consider two countries, each committed to reducing their emissions of greenhouse gases.[6] Let us assume that the costs of emission abatement in one country are independent of emission reduction costs in the other country.[7] Let us first consider a simple model:

(1) $$\min_{R_A} C_A = \alpha_A R_A^2 \text{ s.t. } R_A \geq T_A ; \min_{R_B} C_B = \alpha_B R_B^2 \text{ s.t. } R_B \geq T_B$$

A and *B* denote the two countries. *C* denotes emission reduction costs, *R* emission reduction, and *T* the emission reduction target. The solution to (1) is that $R=T$ for both countries.

Now let us introduce trade in emission permits. Without loss of generality, we assume that Country A imports permits from Country B:

(2) $$\min_{R_A} C_A = \alpha_A R_A^2 + \pi P \text{ s.t. } R_A + P \geq T_A ; \min_{R_B} C_B = \alpha_B R_B{}^2 - \pi P \text{ s.t. } R_B - P \geq T_B$$

P denotes the amount of emission permits transferred from B to A; π is the emission permit price.

The first order conditions of (2) are:

(3a) $$2\alpha_A R_A - \lambda_A = 0$$

(3b) $$\pi - \lambda_A = 0$$

(3c) $$R_A + P - T_A = 0$$

[6] In the following Section we discuss the case of only one greenhouse gas. See Section 5 for the case of more gases.

[7] See Kemfert *et al.* (2001) for alternative assumptions.

(3d) $2\alpha_B R_B - \lambda_B = 0$

(3e) $-\pi + \lambda_B = 0$

(3f) $R_B - P - T_B = 0$

where λ denotes the LaGrange multiplier. (3) solves as:

(4a) $P = \frac{\alpha_A}{\alpha_A + \alpha_B} T_A - \frac{\alpha_B}{\alpha_A + \alpha_B} T_B$

(4b) $\pi = \lambda_A = \lambda_B = 2\frac{\alpha_A \alpha_B}{\alpha_A + \alpha_B} T_A + 2\frac{\alpha_A \alpha_B}{\alpha_A + \alpha_B} T_B$

(4c) $R_A = \frac{\alpha_B}{\alpha_A + \alpha_B} T_A + \frac{\alpha_B}{\alpha_A + \alpha_B} T_B$

(4d) $R_B = \frac{\alpha_A}{\alpha_A + \alpha_B} T_A + \frac{\alpha_A}{\alpha_A + \alpha_B} T_B$

Without trade, the marginal costs of emission reduction are different for both countries. In (1) the marginal costs or the shadow values of the constraint (from here onwards: shadow price[8]) are $2\alpha_A T_A$ and $2\alpha_B T_B$, respectively. With trade, the marginal costs or the shadow prices are the same for both countries and are equal to the permit price.[9] See Table 1.

Both countries gain from trade. For the buying country the costs of emission reduction become smaller and the selling country gets revenue for the exported permits. Therefore, in the buying country the shadow price of emissions reduction goes down, as imported permits expand its options to meet the target. For the selling country, the shadow price goes up, as they reduce emissions in addition to their domestic target for export. This is not immediately obvious from (4). However, the shadow prices without and with trade are only equal at the point at which trade goes to zero:

(5)
$$\begin{aligned} & 2\alpha_B T_B = \lambda_B = \frac{2\alpha_A \alpha_B}{\alpha_A + \alpha_B} T_A + \frac{2\alpha_A \alpha_B}{\alpha_A + \alpha_B} T_B \Leftrightarrow \alpha_B T_B = \alpha_A T_A \\ & \Leftrightarrow \frac{\alpha_B}{\alpha_A + \alpha_B} T_B = \frac{\alpha_A}{\alpha_A + \alpha_B} T_A \Leftrightarrow P = 0 \end{aligned}$$

In words, the shadow price of Country B is higher with than without trade up to the point that Country B stops exporting (P=0) and starts importing.

[8] The costs of slightly changing the emissions target; the λs in (3) and (4).

[9] This is independent of the specific shape of the emission reduction cost functions. However, the ratio would change if there were transaction costs in international permit trade. See below.

Obviously, the less similar the countries' targets and costs, the more room there is for trade, and the greater are the differences between shadow prices with and without trade.

3. Domestic regulation of a bi-national market

Now suppose that the initial targets were set in a cost-benefit analysis. The introduction of international trade in emission permits may induce the buying country to decrease the number of its emission permits. Because the costs of emission reduction are smaller, the buying country can afford a stricter target. The reverse may happen in the selling country. Trade raises its shadow price, and releasing additional permits would lower the shadow price to its marginal benefits of reduced climate change. There is no solution to this. If the selling country adopts a less stringent target, it also lowers the shadow price in the buying country. And, if the buying country adopts a more stringent target, it also raises the shadow prices in the selling country. In fact, the ratio of the shadow prices is always 1:1.[10]

If the selling country increases the number of its emission permits, this is beneficial to their industry, but is at the expense of the environment. If the buying country reduces the number of its emission permits, this is beneficial to the environment, but is at the expense of their industry. If we assume the buying country to be a relatively environmental friendly country, an increase in the number of the emission permits in the selling country would not be received well in the buying country. Suppose the buying country decides to discount emission reduction in the selling country by a factor d, that is, instead of counting an imported tonne of carbon as 1tC it only counts as dtC.

With a carbon discount, the problem looks like:

(6) $$\min_{R_A} C_A = \alpha_A R_A^2 + \pi P \text{ s.t. } R_A + dP \geq T_A; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P \text{ s.t. } R_B - P \geq T_B$$

with $0 \leq d \leq 1$.[11] For given emission reduction targets, total emissions fall by $(1-d)P$. The shadow prices of both countries are given in Table 1, as is their ratio.

Introducing d reduces the shadow price in the selling country, but raises the shadow price in the buying country. In fact, the shadow prices lie somewhere in between what they would have been without trade and with undistorted trade (the total costs are a different story, see

[10] If the ratio of the marginal benefits of emission reduction also equals 1:1, then no trade would occur (provided that the cost functions are quadratic).
[11] The first-order conditions and the solution are given in the appendix.

below). The ratio of shadow prices changes to $1/d$, so that this ratio can in principle also reflect the ratio of the marginal benefits[12] of emission reduction. Introducing or lowering d increases the total costs of the selling country compared to a situation of free trade, so that the buying country can use this as a threat to the selling country not to flood the market with permits – provided, of course that A is willing to pay the price; see below for further discussion.

Besides a quantity instrument, the buying country can also introduce a price instrument, like a tariff. With a tariff, the problem looks as follows:[13]

$$(7) \qquad \min_{R_A} C_A = \alpha_A R_A^2 + t\pi P \text{ s.t. } R_A + P \geq T_A ; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P \text{ s.t. } R_B - P \geq T_B$$

with $t \geq 1$. Total emissions are not affected by a tariff.[14] The shadow prices of both countries are given in Table 1, as is their ratio, which equals $t/1$. Introducing a tariff therefore also allows that the ratio of shadow prices equals the ratio of marginal benefits.

In general, the tariff drives a price wedge between the two national markets. It lowers the price for emission permits in the exporting country and raises it in the importing country but by less than the tariff rate. Country *B* sells less permits to *A*, and at a lower price. However, as with the discount factor *d*, the shadow price of *B* falls and its total costs rise. Therefore, the threat of a tariff can also be used to deter *B* from flooding the market with permits.

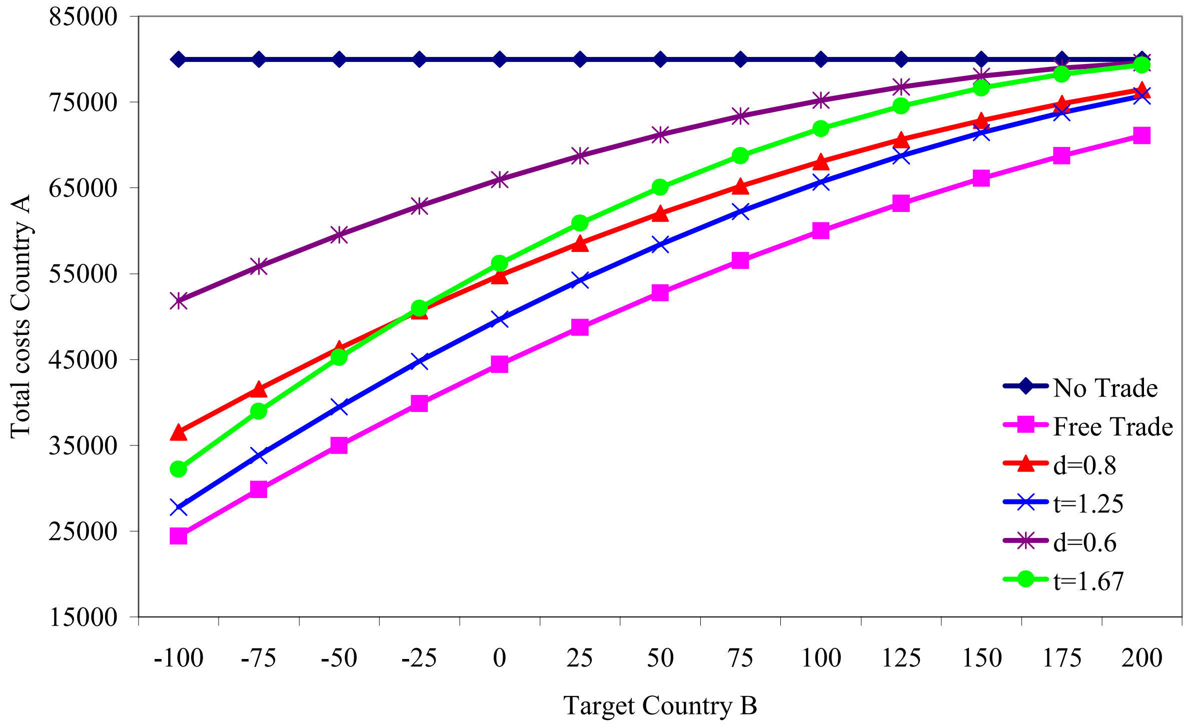
Figure 1 shows the total costs of both countries as a function of the target of the selling country, for the case without trade, with free trade, and two cases with a discount and two cases with a tariff. The costs of both countries always stay below the "no trade" case (with equal targets) regardless of whether trade is regulated or free, and whether discount or tariffs are used for regulation.

For Country B, adopting a lower target decreases costs, and more so when there is the option to export permits. If its target is low enough, or negative (hot air), Country B would even benefit from exporting permits. However, if Country B sets its target too low, it would spoil its own export market, and its benefits would start falling. If Country B's target is low, a

[12] That is, the benefits of reduced climate change.
[13] The first-order conditions and the solution are given in the appendix.
[14] A major difference with the carbon discount rate is that Country A gains revenue by setting a tariff. We assume that the revenue is redistributed to the population without affecting the domestic market for emissions permits.

discount would decrease costs, as a discount would constrain the market and drive up the permit price and Country B's revenue. For higher targets, the constraints on the market would increase the costs of Country B. An equivalent tariff would increase the costs of Country B and is always more expensive than is a discount. A tariff reaps some of B's producer surplus and transfers it to A.

For Country A, a lower target in B implies lower costs if there is trade. A discount would increase Country A's costs, but would keep them below the costs in the no trade case. However, a tariff would also increase costs, but the costs would always stay below the costs of an equivalent discount because of the revenue of the tariff.



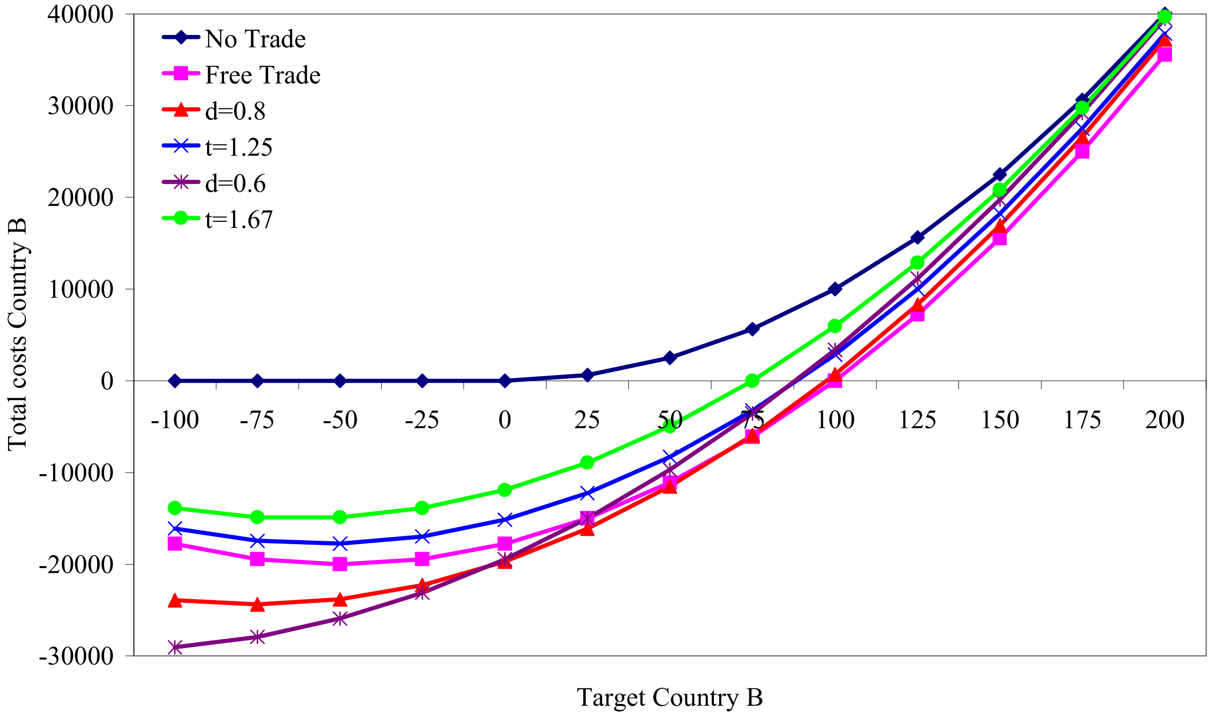


Figure 1. The total costs of Country A (top panel) and Country B (bottom panel) as a function of the emission reduction target of Country B. Six cases are displayed: No trade, free trade, trade with a discount of 0.8 and 0.6, and trade with a tariff of 1.25 and 1.67. The target of Country A is 200; α_A=2; α_B=1.

A carbon discount is not the only quantity instrument. Country A could also limit the amount of imported permits. For example, Country A has to achieve at least 50% of its total emission reduction domestically.[15] With such an import quota the problem looks as follows:

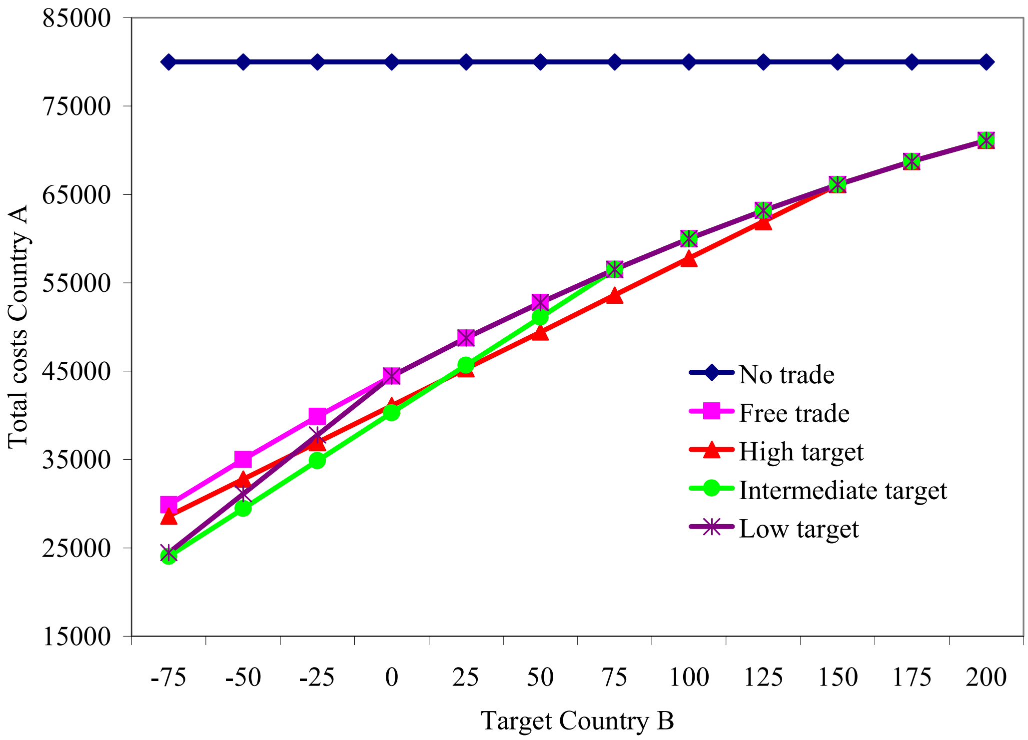
(8) $$\min_{R_A} C_A = \alpha_A R_A^2 + \pi P \text{ s.t. } R_A + P \geq T_A \text{ and } R_A \geq \gamma P; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P \text{ s.t. } R_B - P \geq T_B$$

with $\gamma > 0$.[16] Unlike the carbon discount *d*, total emissions are not affected by the import quota γ. The shadow prices of both countries are given in Table 1, as is their ratio.

Introducing an import quota γ has the same effects on the costs as a carbon discount or a tariff has. Compared to a situation of free trade it reduces the shadow price in the selling country and raises it in the buying country.

[15] A proposal with the same intention was adopted in May 1999 by the European Union Council of Ministers (8346/99) as a strategy to limit on the amount of traded permits with respect to the KP flexibility mechanisms. See Baron *et al.* (1999) or Woerdman (2001).
[16] The first-order conditions and the solution are given in the appendix.

Figure 2 shows the total costs of both countries as a function of the target of the selling country for five different cases: The case without trade, with free trade and with three different cases for import constraints. In general, a lower target in Country B would decrease the permit price and increase the amount of exported permits. If Country A restricts the amount of imported permits, imports would stay constant. For Country B, an import restriction would increase its costs. For Country A, an import quota would decrease the costs,



because the quota reduces the permit price. This is not generally true – the import quantity is also restricted.

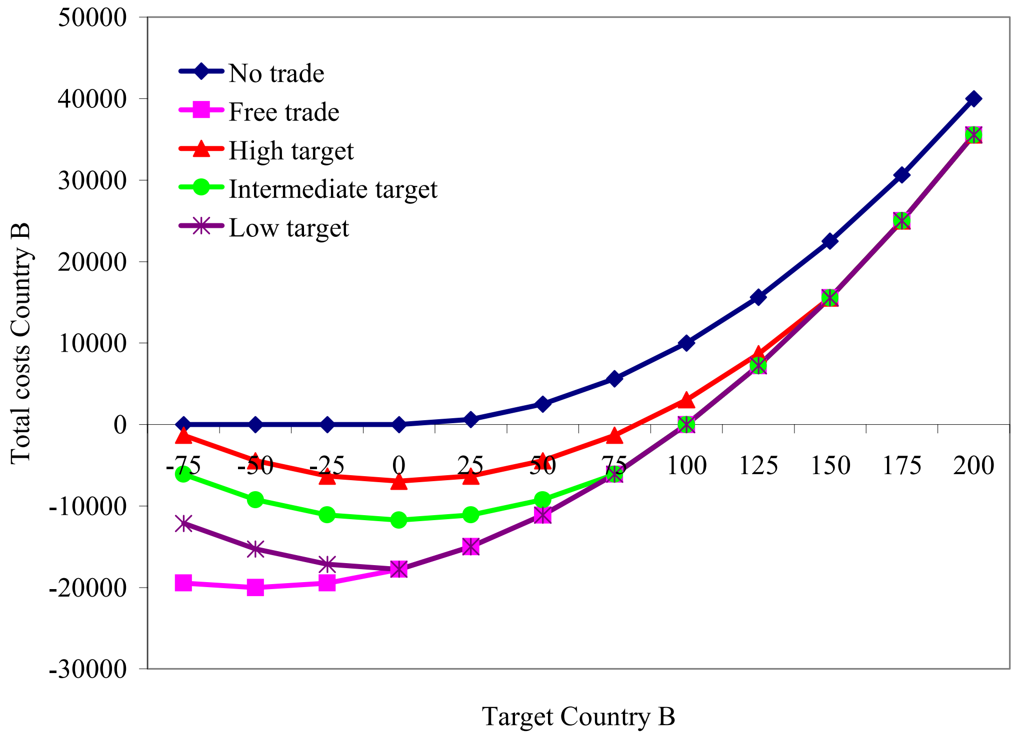


Figure 2. The total costs of Country A (top panel) and Country B (bottom panel) as a function of the emission reduction target of Country B. Five cases are displayed: No trade, free trade, trade with a high domestic emission reductions ($R_A \geq 117$), trade with an intermediate domestic emission reductions ($R_A \geq 92$) and trade with low domestic emission reductions($R_A \geq 67$). The target of Country A is 200; α_A=2; α_B=1.

In Figure 3 displays total costs for both countries as a function of the discount, the tariff (with t=1/d) and the import quota[17]. With a higher tariff or quota or a lower discount, Country A always increases the amount of permits reduced domestically and lowers the amount of imported permits. That increases costs, if the permit price is unaffected. Country A loses out from both a tariff and a discount, but a tariff is always less expensive than a discount. Country A's costs increase for tariffs, discounts and larger quotas, but always stay below the no trade scenario. However, Country A gains from a small import restriction, as seen above. However, if Country A sets γ high and lowers the amount of imported permits significantly compared to a free trade situation they would increase their costs, just as a tariff or discount would do. In setting import restrictions there is a trade-off between lowering the permit price and stifling imports.

[17] The equation for the relation from discount and tariff to the quota follows from (A9). See also Table 1.

A tariff is always more expensive to Country B than a discount. An import quota is always the most expensive instrument to Country B. The reason is, that the quota lowers the permit price more than a discount and a tariff, and at the same time it lowers the amount of traded permits also more than both discount or tariff.

The effects shown in Figure 3 are even more pronounced for both countries if B's target is weaker or its emission reduction costs lower. However, Country B can gain from a discount[18] if its emission reduction target is low or negative.[19] A discount leads to an increase in total emission reduction even though the emission reduction targets are unchanged. In cases where Country B has a low target, a small discount (*d* close to 1) increases the amount of traded permits as well as the permit price relative to a free trade situation (*d*=1). From B's perspective, there is an optimal discount rate ($d < 1$).

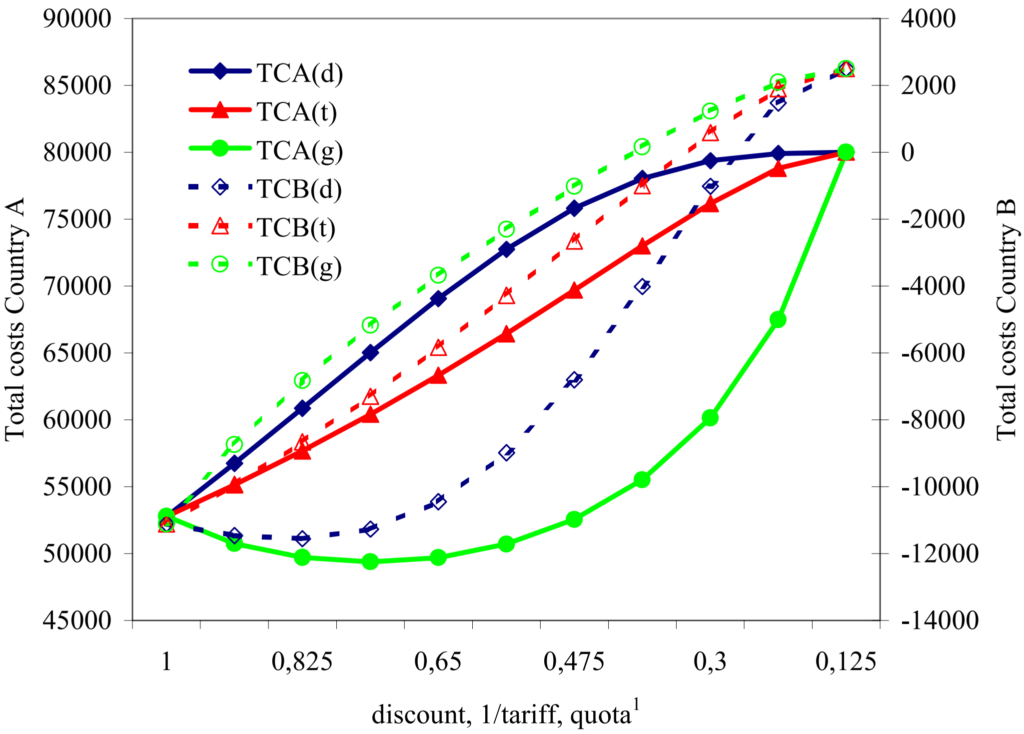


Figure 3. The total costs of Country A (left axis) and Country B (right axis) as a function of the discount, tariff and quota. The point on the far left corresponds to the situation of free trade, the far right point to the situation of no trade. The target of Country A is 200; B's target is 50; α_A=2; α_B=1. [1]The equation for the relation between quota and discount or tariff follows from (A9). See also Table 1. For R_A=200 and R_B=50; γ varies from 0.7 to 9.

[18] See the lower left side of Figure 3.
[19] Low target stands here for a situation where Country B would have no costs but net benefits with free trade. See Figure 1.

Figure 4 shows the shadow prices of both countries as a function of the discount, the tariff (with t=1/d) and the import quota.[20] Figure 4 confirms that trade increases the shadow price of emission control in Country B, and decrease the shadow price in Country A. Restrictions on trade make this less pronounced; indeed, if the discount, tariff or quota is set so high that trade ceases, the shadow prices of both countries return to their no trade levels.[21] A tariff and a quota make B's shadow price fall faster than does a discount; this is independent of parameter choice.[22] A discount makes A's shadow price rise faster than does a tariff or quota; again, this is independent of the parameters. These effects are slightly more pronounced if B's target is weaker or its emission reduction costs lower.

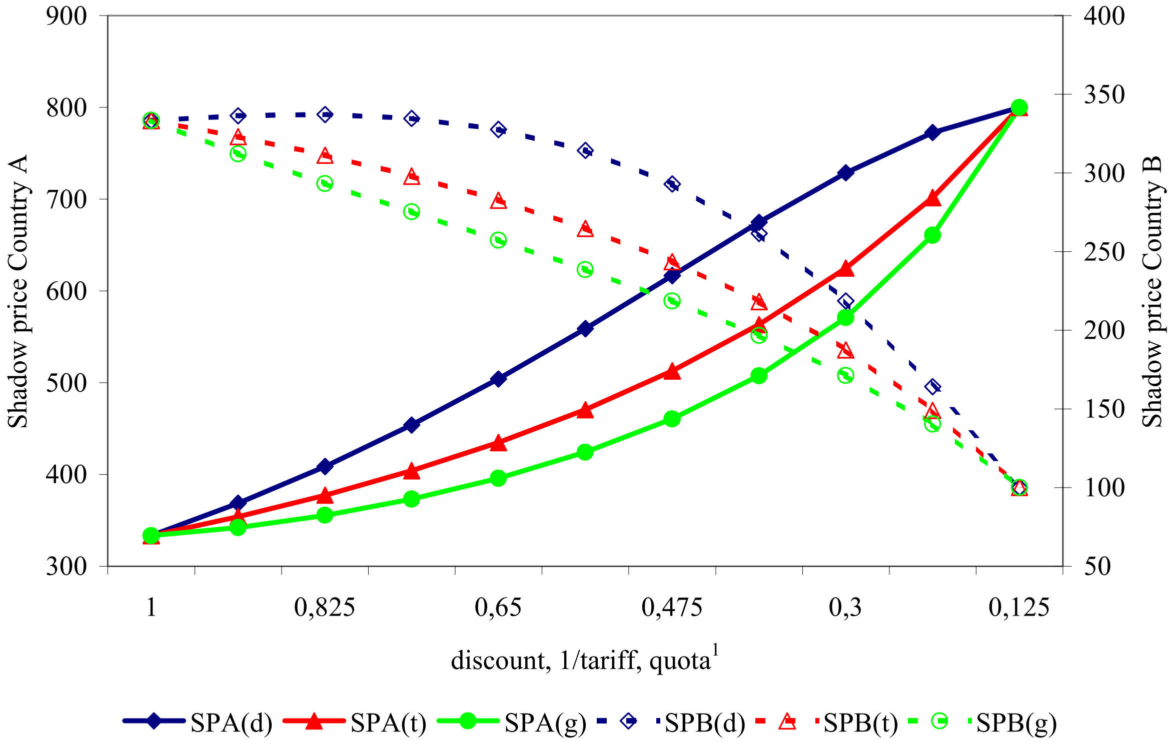


Figure 4. The shadow prices of Country A (left axis) and Country B (right axis) as a function of the discount, tariff and import quota. The point on the far left corresponds to the situation of free trade, and the far right to the situation of no trade. The target of Country A is 200; B's target is 50; α_A=2; α_B=1. [1]The equation for the relation between quota and discount or tariff follows from (A9). See also Table 1. For R_A=200 and R_B=50; γ varies from 0.7 to 9.

[20] The equation for the relation between quota and discount or tariff follows from (A9). See also Table 1.
[21] This can be seen by solving P=0 for d and t in Equations (A3a) and (A6a), respectively, and substituting the results in Equations (A3b-c) and (A6b-c), respectively. For γ, this can be directly seen from (A9a).
[22] A low target of Country B combined with a d at approximately 1 can increase Country B's shadow price. See above.

4. Environmental integrity

One of the reasons why Country A would regulate trade is to prevent Country B from issuing more and more permits. So far, we avoided the question whether Country A is able to do so. We did show that a discount, would lead to a loss to Country B if it has a relatively strict target.[23] On the other hand, Country B would gain if it sets a lower target. The trade-off between the two effects is shown in Figure 5. We assume that if Country B lowers its target, Country A increases the discount so that total emissions stay constant[24], preserving "environmental integrity". The benefits of a lower target would be greater than the costs of a higher discount. Only if Country B lowers its target substantially, could Country A deter Country B from issuing additional permits.

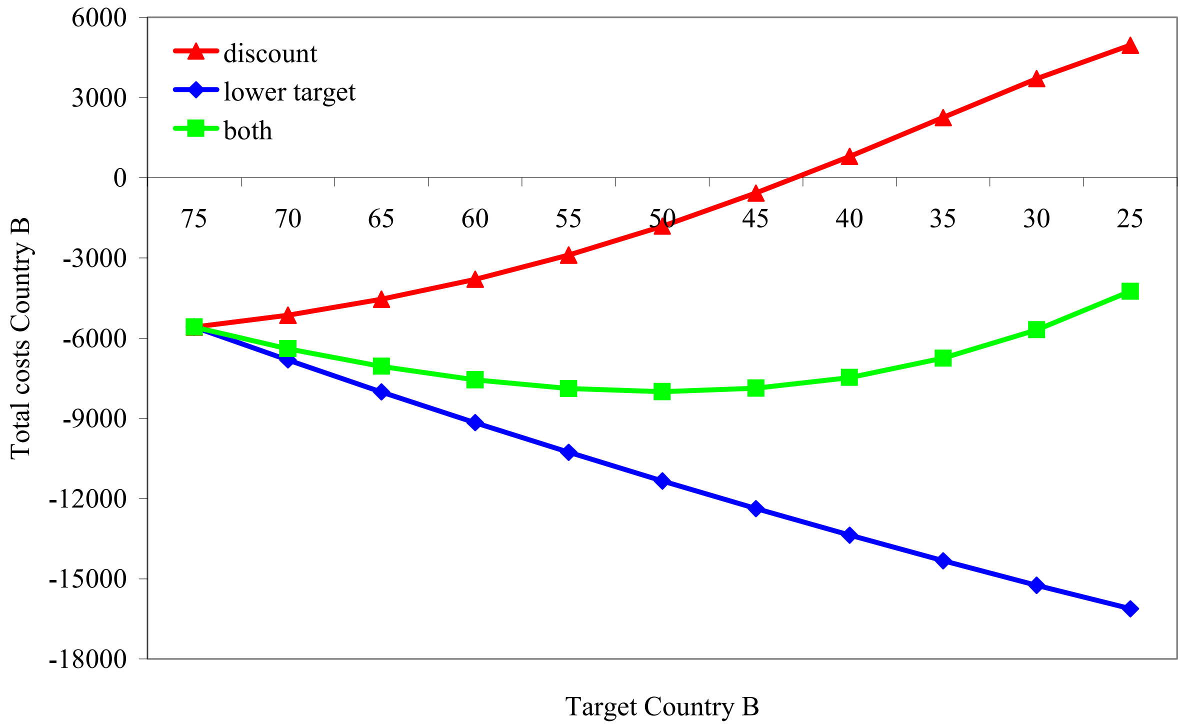


Figure 5. The total costs of Country B for three cases. In the first case ("discount"), B's target is kept constant (at 75) and the carbon discount is varied (from 0.75 to 0.26). In the second case ("lower target"), the discount is kept constant (at 0.75) and B's target is varied (from 75 down to 25). In the third case ("both"), both the discount and B's target are varied and exactly offset each other with regard to total emissions. The target of Country A is 200; α_A=2; α_B=1.

[23] If Country B has a loose target, it would gain if Country A installs a discount – in that case, a discount would only encourage Country B to loosen its target further.

[24] The equation for this follows straightforwardly from (A3).

Country A can influence total emissions with a discount as it drives a wedge between total emissions and total emission reduction targets. Total emission stay always below the emission reduction targets. With a tariff or a quota, total emissions are unaffected. These instruments are therefore not suited to preserve "environmental integrity". However, a discount is a bad deterrent. Therefore, we turn our attention to tariffs and quota as a means for Country A to regulated the amount of imported permits.[25]

Figure 6 shows the trade-off between the two effects. The target of Country B is varied, and the intensity of the instrument of Country A is chosen such that the amount of imported permits stays the same. For Country A, costs differ substantially between the three instruments. A discount is more expensive than a tariff, and a tariff is more expensive than a quota.

The amount of traded permits is equal for a discount, a tariff and a quota (by construction), and the permit price is equal as well. So, for Country B, the total costs are the same, regardless of the instrument. As can be seen from Figure 6, the combination of a lower target and a more stringently regulated market increases the costs of Country B

So, if Country A aims at the import of permits, it can deter Country B from flooding the market with permits. Country A's preferred instrument is an import quota.

[25] The equation for this follows from (A3), (A6) and (A9).

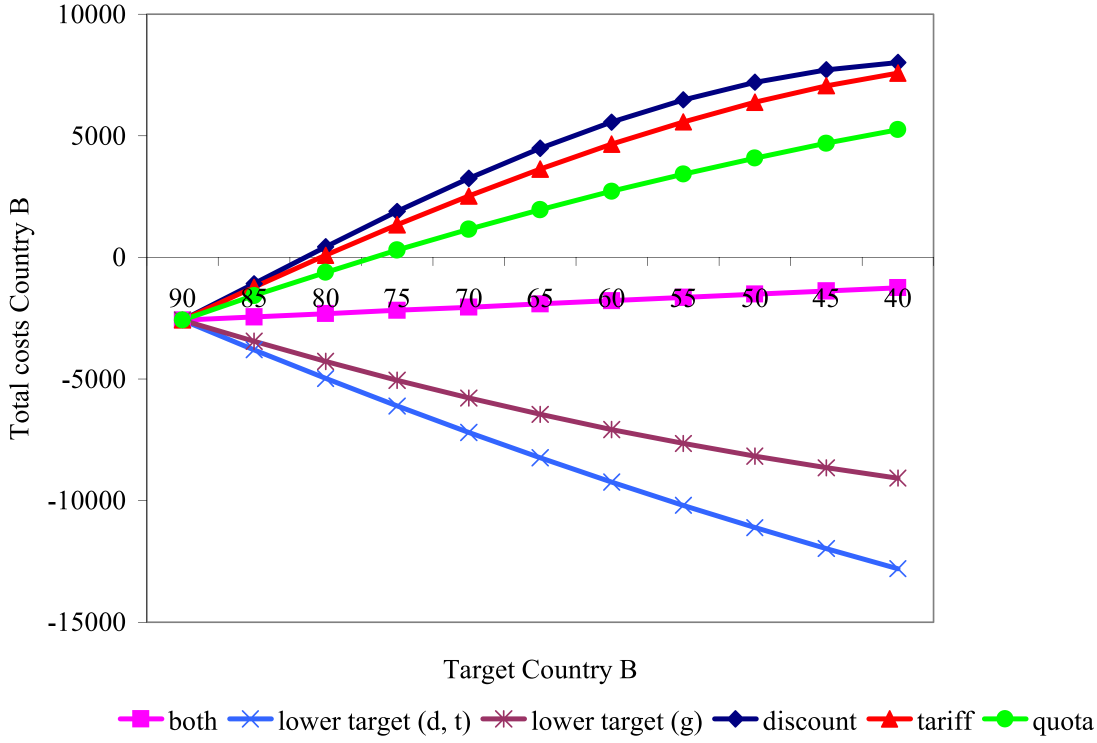


Figure 6. Total costs of Country B for three cases. In the first case ("tariff", "discount" and "quota"), B's target is kept constant (at 90) and both tariff, discount and quota are varied (tariff from 1 to 3.15, discount from 1 to 0.25, quota from 0.94 to 2.75). In the second case ("lower target"), tariff, discount and quota are kept constant and B's target is varied (from 90 to 40). In the third case ("both"), both the tariff, the discount respectively the quota and B's target are varied and exactly offset each other with regard to the amount of traded permits. The target of Country A is 200; α_A=2; α_B=1.

5. Compliance and liability

So far, we have assumed that all participants in emission permit trading comply with their regulations. However, the implementation of a strong compliance system is a crucial aspect of any effective environmental regulation. Regarding emissions trading, a weak compliance system would increase the risk of non-compliance by overselling.[26]

[26] Overselling could occur unintentionally or willfully (Nordhaus *et al.* 2000a).

The literature on compliance and liability for greenhouse gas emission permits is placed in the context of the Kyoto Protocol, that is, trade between countries under international regulation.[27] A range of liability rules addressing the risk of overselling have been proposed all intending to limit the traded permits to quantities in surplus to sellers' compliance needs.[28] These rules can be divided into three groups: (1) the seller, (2) the buyer or (3) both are held liable for non-compliance by the seller. Unfortunately, no first best rule can be determined. Furthermore, all are likely to have a significant impact on the emissions trading market.[29]

The buyers' liability leads to a cancellation or devaluation of traded permits if the seller is in non-compliance. Different prices would occur, since buyers would prefer sellers likely to achieve compliance. In addition, it might increase transaction costs and thereby lower the volume of trade (see Zhang, 2001).

Instead, sellers' liability would create a homogenous market with more trade, because any traded permit is valid for the buyer. Consequently, sellers' liability requires an efficient non-compliance mechanism to avoid overselling. To deter economic incentives for overselling financial penalties need to be higher than the potential gains from overselling.[30] But since participation is voluntary, internationally agreed enforcement mechanisms are likely to be ineffective. Penalties for non-compliance would be weak. Additionally, even if strong domestic compliance instruments exist, they are difficult to put into force internationally (see Werksman, 1999).

In certain cases, sanctions are limited or participants could not be held completely liable for non-compliance ex-post, one option is to use eligibility requirements for participation to prevent non-compliance (see Michell, 1994; Zhang and Nentjes, 1998, set up certain minimum criteria). Other approaches to ensure compliance by the seller opt for a limitation of sales (e.g. annual retirements[31]), for a limitation of trade to surplus quotas (e.g. permanent

[27] Penalties are for non-compliance are not yet defined under the Protocol (UNFCCC 2000, UNFCCC 2001). For a discussion of the progress up to Marrakesh, see Torvanger (2001).
[28] A survey of proposals is presented in Baron (1999) and Nordhaus *et al.* (2000a).
[29] To deal with the advantages and disadvantages of the above proposals a combination of different rules is suggested. Zhang (2001) favours a combination of preventative measures with strong end-of-pipe punishments to ensure compliance.
[30] The quantitative analysis of Haites and Missfeldt (2001) suggests that sufficient penalties must be effectively enforced and at least 2.3 times the expected price.
[31] Under an annual retirement system a party must annually set aside quotas equal to its cumulative emissions; see CCAP (2000).

reserves[32]) or for a restoration[33] (compliance reserves[34], escrow accounts[35] or compulsory insurances[36]). To avoid the shortcomings of a pure seller or buyers' liability system the „traffic light" approach was suggested, where parties would usually trade under sellers' liability (green light).[37]

However, our case is different, as we have firms operating under domestic regulation. Domestically, each firm would have to demonstrate to the regulator that its actual emissions do not exceed its total amount of permits. If a firm is out of compliance, for instance because it has sold too much, that is the problem of that firm, and not a problem of the firms it has traded with. Domestically, sellers' liability would apply.

If emission permits are also traded across borders, the situation is more complicated. If a firm in Country A buys permits from a firm in Country B, and the firm in Country B is out of compliance, the regulator in Country A may decide one of two extremes (and, of course, anything in between). If the regulator in Country B appropriately enforces its emissions trading, the regulator in Country A may well accept the trade as valid. (This is still sellers' liability.) If the regulator in Country B turns a blind eye to firms exporting permits, the regulator in Country A may decline the imported permits, and treat the importers as if they are out of compliance. This is buyers' liability. The importing firms may of course decide to seek compensation from the exporting firms, if the legal framework would allow them to. Ultimately, firms must justify their emissions to the domestic regulator, so that buyers' liability applies to permits acquired from abroad.

[32] The permanent reserve concept states that parties must permanently hold a share of its total permits. These quotas could only be traded if they are identified as surplus and therefore not needed to ensure the seller's compliance; see Nordhaus *et al*. (2000b) and CIEL (2000).
[33] Following Haites and Missfeldt (2001).
[34] A compliance reserve requires that a percentage of each trade has to be put into an account. If the seller is in compliance the permits are returned. A comparison of the compliance reserve and the escrow account is provided by Kerr (2000).
[35] Under the escrow account approach the revenue from the initial sale of permits is deposited into an account to cover the risk of non-compliance by the seller. The seller receives the proceeds when compliance has been established. See Haites (1998).
[36] A compulsory insurance taken out by the sellers would lead to a homogenous market. However, individual insurance premium would depend on the seller's probability of non-compliance. A higher risk of non-compliance will lead to a higher premium. See Hargrave *et al.* (1999) and Zhang (2001).
[37] The light would turn to „yellow" if a party's non-compliance problems are identified. During this period the buyer would be held liable. On condition that the compliance problem is not addressed, the „red light" is turned on and this party would be not allowed to trade. As a result, parties would own green and yellow permits. Proposed by Goldberg *et al.* (1998) and more recently by Yamin *et al.* (2001). For a discussion of this proposal see CIEL (1999).

In Sections 2 and 3, we assume that every company complies with the regulations, and that all trades are valid. We also assume that companies report to their regulator, comparing their actual emissions to their emission permits. This implicitly assumes buyer's liability. Under buyers' liability, buyers would screen sellers before trading.[38] A "carbon rating" would emerge, distinguishing trustworthy sellers from less reliable ones, just like credit ratings distinguish reliable borrowers. The carbon rating could be reflected in the price buyers are willing to pay. If companies abroad are systematically less reliable than compatriots, this would drive a price wedge between the countries, just like a tariff does (see 7), but now of course without the benefits of revenue collection. Alternative, potential non-compliance could be reflected in the quantity purchased. Let us again assume that there are systematic differences between the countries.[39] Let p denote the probability of the seller not complying. Therefore, with a p greater than zero the demand for unreliable permits would fall.

Under buyers' liability the problem looks like:

$$(8) \qquad \min_{R_A} C_A = \alpha_A R_A^2 + \pi P \text{ s.t. } R_A + (1-p)P \geq T_A ; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P \text{ s.t. } R_B - P \geq T_B$$

with $0 \leq p \leq 1$.[40] In fact, the carbon exchange rate d has the same effect as the "carbon rating" (1-p), if Country B's companies have a lower standing in the carbon rating. Table 1 shows the shadow prices of both countries.

Under sellers' liability, the consequence for a buyer being out of compliance would be borne by the seller.[41] Assuming, as is likely, that this imposes costs, the supply of emission permits would go down. If, as also likely, settling foreign claims is more expensive than settling domestic ones, a wedge between the domestic markets would again emerge. If this is reflected in the price, the result is similar to introducing a tariff (but, again, without the revenues). Alternatively, permit sellers could play safe, and plan to overcomply. Let μ denote for the risk of non-compliance by the seller set by the selling country.

[38] Companies may be fined if out of compliance. If not, companies presumably would need to buy additional permits, loosing the money paid for the invalid permits.

[39] If companies would doubt all purchased permits, they would overcomply in general, which should be modeled as an increase in the emissions targets T_A and T_B.

[40] The first-order conditions and solution are given in the appendix.

[41] Under sellers' liability, the regulator of the seller of permits would hold the seller accountable if the buyer complains to the seller's regulator. (This would happen if the regulator of the buyer, perhaps alerted by the regulator of the seller, finds the buyer out of compliance.) With international trade, the regulator of the seller should be open to domestic complaints as well as complaints from abroad. This does not require an international treaty. Alternatively, the regulator of the seller may find the seller out of compliance, and force it to compensate all, domestic and abroad, to whom it sold permits. This does not require an international treaty either.

The problem then looks like:

(9) $$\min_{R_A} C_A = \alpha_A R_A^2 + \pi P \text{ s.t. } R_A + P \geq T_A ; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P \text{ s.t. } R_B - (1+\mu)P \geq T_B$$

with $\mu \geq 0$.[42] Total emissions fall by μP. Table 1 shows the shadow prices of both countries, and the ratio of the two. That ratio is $(1+\mu)/1$. Sellers' liability, like buyers' liability, dictates the ratio of the shadow prices; this ratio is only by coincidence equal to the ratio of the marginal benefits of emission control.

Figure 7 compares the gains of trade under sellers' and buyers' liability to a situation of free trade.[43] Country A always prefers sellers' liability, which is obvious. Country B prefers buyers' liability if its target is loose, and sellers' liability if its target is stricter. The reason that Country B prefers to be liable itself is as follows. Sellers' liability is more expensive to B *at the margin* (see below). However, buyers' liability constrains the market much more than does sellers' liability (see below), and this is more costly to Country B than are the costs of bearing liability. This is independent of parameter choice. For both countries, the differences between buyer and sellers' liability are greater if the target (of B) is stricter, but this matters more to B than it does to A. Both countries are better off, if p or μ are close to zero, that is, the risk of non-compliance is fairly low. However, if the target is stricter, and the market is tighter, the losses due to uncertainty are larger.

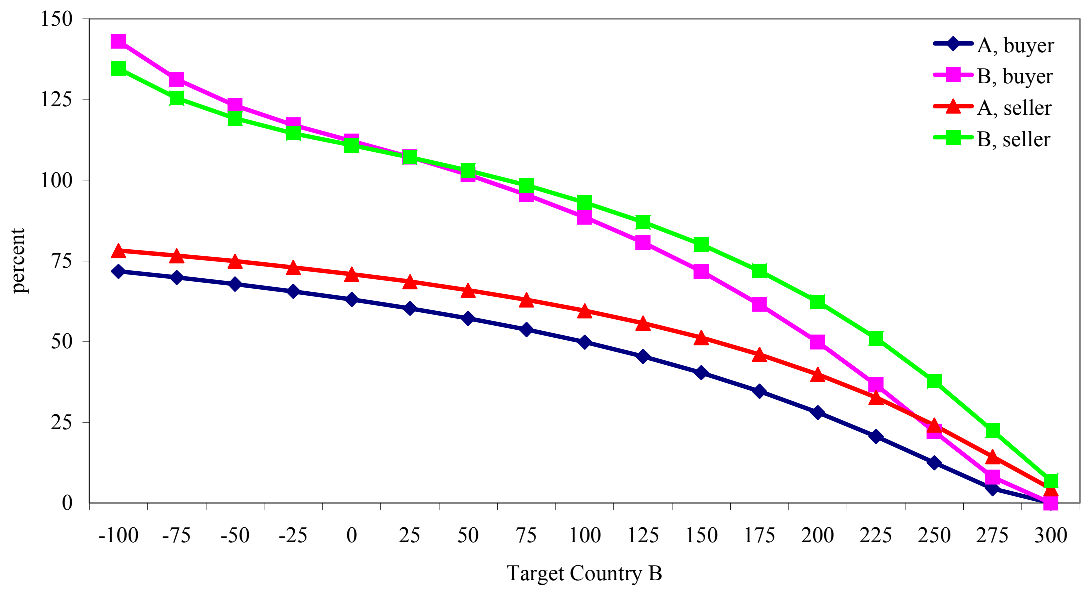


Figure 7. Relative gains of trade for Country A and Country B under sellers' or buyers' liability as a function of the tightness of the market; the target of Country A is always 200,

[42] The first-order conditions and solutions are given in the appendix.

[43] Free trade is the situation where the selling country fully complies 100% with their emission reduction target and no risk of non-compliance occurs (p=μ=0).

B's target varies. The gains of trade with liability as a percentage of the gains without liability are displayed. α_A=2; α_B=1; p=μ=0.25.

The effect on the marginal costs of Country A is not surprising. See Figure 8. Both sellers' and buyers' liability lead to higher marginal costs compared to the situation of free trade and lower marginal costs than in the case of no trade. As Country A has to bear the costs, the marginal costs under buyers' liability are higher than under sellers' liability. Country B would have higher marginal costs if it is held liable for non-compliance. That is also as one would expect.

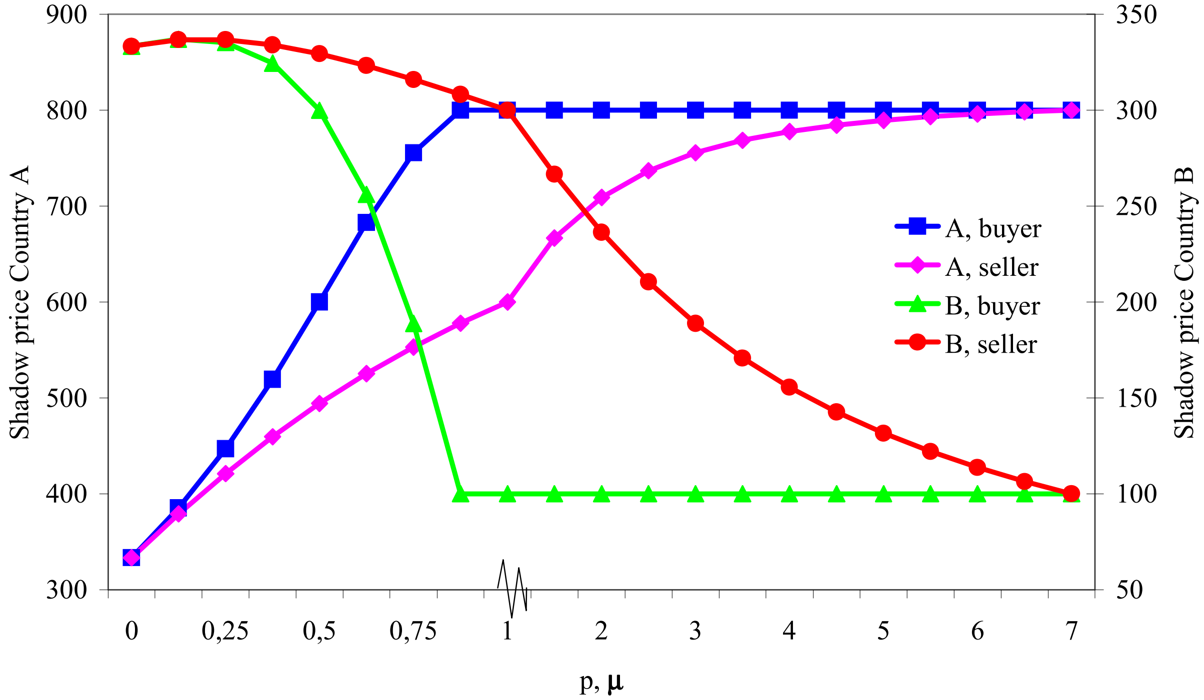


Figure 8. The shadow prices of Country A (left axis) and Country B (right axis) under sellers' and buyers' liability as a function of the chance of non-compliance. The point on the far left corresponds to the situation of free trade, and the far right point to the situation of no trade. The target of Country A is 200; B's target is 50; α_A=2; α_B=1.

As noted above, the market is far more responsive to buyers' liability than it is to sellers' liability. Under buyers' liability, the market breaks down at

$$(10) \qquad P = 0 \Leftrightarrow (1-p)\alpha_A T_A = \alpha_B T_B \Leftrightarrow p = 1 - \frac{\alpha_B T_B}{\alpha_A T_A}$$

whereas, under sellers' liability, at

(11) $$P = 0 \Leftrightarrow \alpha_A T_A = (1+\mu)\alpha_B T_B \Leftrightarrow -\mu = 1 - \frac{\alpha_A T_A}{\alpha_B T_B}$$

and, without compliance problems, at

(12) $$P = 0 \Leftrightarrow \alpha_A T_A = \alpha_B T_B$$

Recall that $\alpha_A T_A > \alpha_B T_B$, otherwise permits would flow from Country A to Country B. So, compliance problems restrain the market (as one would expect), and this effect is more pronounced with buyers' liability than with sellers' liability. The reason is that buyers' liability constrains the short end of the market (the buyer) while sellers' liability constrains the long end of the market (the seller). The same chance of non-compliance (p=-μ), therefore has proportionally a larger effect on the buyers' side than on the sellers' side.

So far, we assumed that country A does not regulate trade, for example to avoid contradicting their more ambitious target with relatively cheap emission permits from B. Below, we examine the relation between buyers' and sellers' liability and the policy instruments of a discount, a tariff or a quota.[44] The equations are straightforward combinations of the ones above. The optimization problems are given in the appendix, together with the first-order conditions and the solutions. Table 1 summarizes some of the results.

Combining sellers' liability or buyers' liability with a carbon discount, a tariff or an import quota has the expected effect on the shadow prices of both countries. For example, liability or regulation increases the shadow price of Country A, and liability plus regulation increases the shadow price more. A discount rate increases A's shadow price faster than does a discount if there are no liability issues, and the same is true with liability issues, regardless of whether the buyers or the sellers of permits are liable for non-compliance. And so on. The same is true for the total costs.

As shown above, both liability and regulation reduce the size of the market, and restrain the range of parameters for which there is any trade. The same is true for liability plus regulation. Figure 9 displays the discount and the tariff at which the market breaks down (P=0) as a function of the uncertainties underlying buyers' and sellers' liability. Liability constrains the room for regulation; the greater the uncertainty about traded permits, the less room there is to regulate the market with a tariff or discount. As before, the trade-off between tariff and

[44] The first-order conditions and the solutions are given in the appendix.

discount is $d=1/t$, regardless of whether buyers or sellers are liable. Also, buyers' liability constrains the market more than does sellers' liability, regardless of whether the market is regulated with a tariff or a discount.

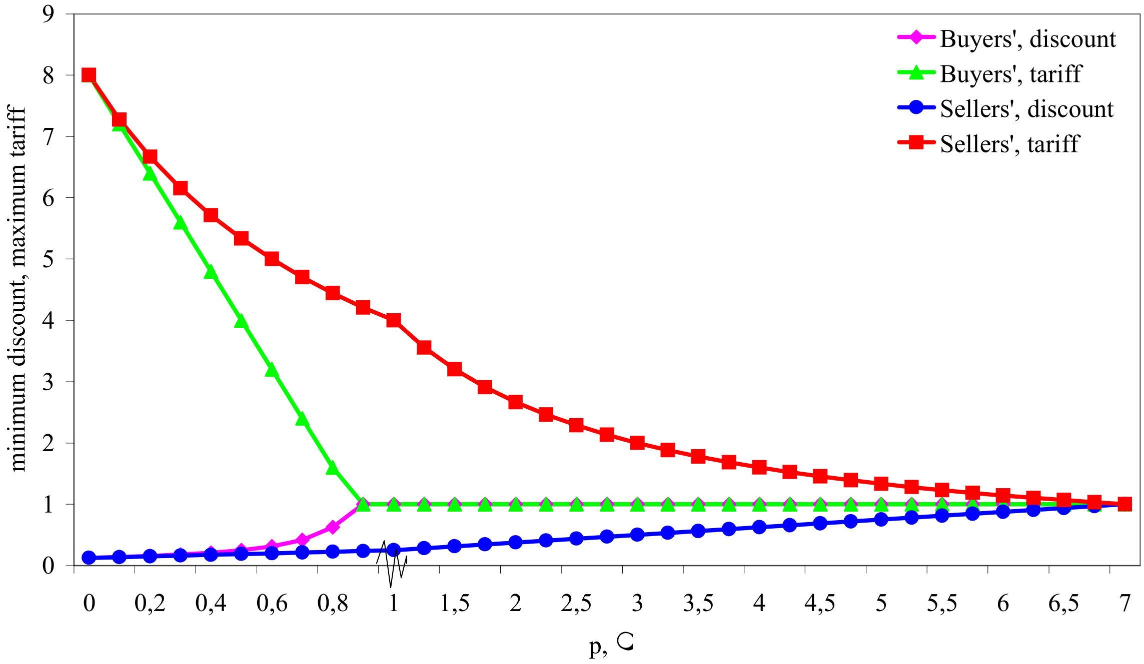


Figure 9. The minimum discount (the d for which P=0) and the maximum tariff (the t for which P=0) as a function of the uncertainty (p and μ, respectively) underlying buyers' liability and sellers' liability. The target of Country A is 200; B's target is 50; α_A=2; α_B=1.

An import quota would not stop trade, unless the restriction is that all emission permits are domestic, that is, $\gamma \to \infty$ in (A18) and (A27).

6. Extensions to the model

The model of the previous section is quite simple. In this section, we discuss possible extensions to the model, without fully solving them.

So far, we restricted ourselves to the reduction of one greenhouse gas only. Now consider the case of multiple gases, say methane and carbon dioxide.[45] If we assume that both countries allow complete substitutability between carbon dioxide and methane, then the domestic market behaves as if there were one gas only. Substitution between carbon dioxide and methane would be regulated with some equivalence factor, such as the Global Warming

[45] The arguments readily carry over to the case of more gases, but the exposition would be far more complex.

Potential. If both countries use the same equivalence factor, the international market in emission permits would behave as if there were one gas only.

However, if the countries use different equivalence factors – say,Country A says that 1 tonne of methane is worth 20 tonnes of carbon dioxide, and Country B says the 1 tonne CH_4 is worth only 10 tonnes CO_2 – then the situation is different. Consider the case in which both countries issue permits for CO_2-equivalent emissions, not for CO_2 and CH_4 separately. Then, from the perspective of Country A, Country B overregulates. In the eyes of the regulator in A, and in the eyes of the companies reporting to it, a permit issued by B is worth more than a permit issued by A. This situation is reverse from B's perspective. The market, or the regulator would introduce a "carbon exchange rate" between the countries, which behaves the same as the d in (6). The main difference is that, in this case, d may be greater than one.

A similar effect would occur if the two countries use different monitoring and enforcement mechanisms. Permits issued by the more stringent regulator would acquire a premium in the more lenient country. The analysis proceeds as before.

The international market assures that permit prices are equal in both countries, or perhaps differ by a fixed factor determined by the d of (6). Typically, compliance is enforced with economic penalties, often proportional to the amount emitted in excess of the total permits. Companies choose between buying a permit and paying the penalty. Essentially, proportional penalties put a cap on the marginal costs of emission reduction. Phrased differently, if the price in the emission permits market is too high, the regulation is transformed into a tax regime. In a domestic market, this is fine.

In an international market, it is not. Suppose the market price hits the penalty in Country B. Suddenly, B has an infinite supply of permits at a fixed price (the penalty). If not regulated, this price is also the price in Country A. Country B sets the effective penalty in A. This may not be what A had in mind. Again, the carbon exchange rate d may help out. In this case, A would set d such that B's permits are offered at a price of the penalty in A. Alternatively, A could use a tariff t (see 7) to drive up the price of imported permits or a quota (see 8) to restrict the imported amount.

So far, the analysis was limited to the case of two countries only. A lot of the results carry over to the case with more than two countries, although the analysis becomes considerably more complex. The real complication lies in arbitrage. If countries keep their targets and other regulations fixed, the market would solve that. However, if countries change their targets and regulations – for example, to manipulate marginal emission reduction costs or to prevent too much import from certain other countries – they would have to reckon with fairly complex feedback on their action. Arguably, the more countries there are in the market, the less control each country has over its emission reduction policy.

7. Discussion and conclusion

This paper considers domestic markets of tradable permits for greenhouse gas emission control, particularly the question under what conditions domestic markets would and should merge to become an international market. We focus on the case of two countries.

We show that international trade benefits both countries. This is hardly surprising, as all trade has this effect. We also show that the international trade is environmental neutral, that is, total emissions stay the same. This is the case with all tradable permit systems. However, we argue that there might be pressure in the importing country to strengthen its emission reduction policy, while in the exporting country might be an incentive to weaken its policy.

The importing country can regulate the market with price (a "carbon tariff") and quantity (a "carbon discount" or "import quota") instruments. This can be done to smoothen regulatory differences between the countries (e.g., monitoring and enforcement), but also to deter the exporting country from issuing additional permits for export only; if the latter is the goal, the importing country should seek to keep the amount of imported permits constant, rather than the total emissions. Regulation constrains the market, and makes both countries in most cases worse off. Structural differences in the reliability of domestic and foreign permits, and structural differences in settling non-compliance claims in the home country and abroad would also constrain the market, but less so for sellers' liability than for buyers' liability. Both the importing and the exporting country would prefer that the permit seller is liable in case of non-compliance.

The analysis presented here needs extension in at least three directions. Firstly, more countries need to be considered. Secondly, the choice of domestic emission standards needs so be to made explicit. Thirdly, the domestic market of emission permits needs to be modeled. These tasks are deferred to future research.

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APPENDIX

The problem of the binational market with a carbon discount rate is:

(A1) $\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ s.t. $R_A + dP \geq T_A$; $\min_{R_B} C_B = \alpha_B R_B^2 - \pi P$ s.t. $R_B - P \geq T_B$

with $0 \leq d \leq 1$.

The first order conditions of (6) are:

(A2a) $2\alpha_A R_A - \lambda_A = 0$

(A2b) $\pi - \lambda_A d = 0$

(A2c) $R_A + dP - T_A = 0$

(A2d) $2\alpha_B R_B - \lambda_B = 0$

(A2e) $-\pi + \lambda_B = 0$

(A2f) $R_B - P - T_B = 0$

Total emissions fall by (1-*d*)*P*.

(A2) solves as:

(A3a) $P = \frac{\alpha_A d}{\alpha_A d^2 + \alpha_B} T_A - \frac{\alpha_B}{\alpha_A d^2 + \alpha_B} T_B$

(A3b) $\pi = \lambda_B = \frac{2\alpha_A \alpha_B d}{\alpha_A d^2 + \alpha_B} T_A + \frac{2\alpha_A \alpha_B d^2}{\alpha_A d^2 + \alpha_B} T_B$

(A3c) $\lambda_A = \frac{2\alpha_A \alpha_B}{\alpha_A d^2 + \alpha_B} T_A + \frac{2\alpha_A \alpha_B d}{\alpha_A d^2 + \alpha_B} T_B$

(A3d) $R_A = \frac{\alpha_B}{\alpha_A d^2 + \alpha_B} T_A + \frac{\alpha_B d}{\alpha_A d^2 + \alpha_B} T_B$

(A3e) $R_B = \frac{\alpha_A d}{\alpha_A d^2 + \alpha_B} T_A + \frac{\alpha_A d^2}{\alpha_A d^2 + \alpha_B} T_B$

If *d*=1, (A3) returns to (4).

With a tariff, the problem looks as follows:

(A4) $\min_{R_A} C_A = \alpha_A R_A^2 + t\pi P$ s.t. $R_A + P \geq T_A$; $\min_{R_B} C_B = \alpha_B R_B^2 - \pi P$ s.t. $R_B - P \geq T_B$

with $t \geq 1$.

The first order conditions of (A4) are:

(A5a) $2\alpha_A R_A - \lambda_A = 0$

(A5b) $t\pi - \lambda_A = 0$

(A5c) $R_A + P - T_A = 0$

(A5d) $2\alpha_B R_B - \lambda_B = 0$

(A5e) $-\pi + \lambda_B = 0$

(A5f) $R_B - P - T_B = 0$

Total emissions stay the same. This solves as:

(A6a) $P = \frac{\alpha_A}{\alpha_A + \alpha_B t} T_A - \frac{\alpha_B t}{\alpha_A + \alpha_B t} T_B$

(A6b) $\pi = \lambda_B = \frac{2\alpha_A \alpha_B}{\alpha_A + \alpha_B t} T_A + \frac{2\alpha_A \alpha_B}{\alpha_A + \alpha_B t} T_B$

(A6c) $\lambda_A = \frac{2\alpha_A\alpha_B t}{\alpha_A + \alpha_B t} T_A + \frac{2\alpha_A\alpha_B t}{\alpha_A + \alpha_B t} T_B$

(A6d) $R_A = \frac{\alpha_B t}{\alpha_A + \alpha_B t} T_A + \frac{\alpha_B t}{\alpha_A + \alpha_B t} T_B$

(A6e) $R_B = \frac{\alpha_A}{\alpha_A + \alpha_B t} T_A + \frac{\alpha_A}{\alpha_A + \alpha_B t} T_B$

If t=1, (A6) returns to (3).

With an import quota, the problem looks like:

(A7) $\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ s.t. $R_A + P \geq T_A$ and $R_A \geq \gamma P; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P$ s.t. $R_B - P \geq T_B$

with $\gamma > 0$.

The first order conditions are:

(A8a) $2\alpha_A R_A - \lambda_A - \lambda_C = 0$

(A8b) $\pi - \lambda_A + \lambda_C \gamma = 0$

(A8c) $R_A + P - T_A = 0$

(A8d) $R_A - \gamma P = 0$

(A8e) $2\alpha_B R_B - \lambda_B = 0$

(A8f) $-\pi + \lambda_B = 0$

(A8g) $R_B - P - T_B = 0$

Total emissions stay the same.

This solves as (4), unless $R_A < \gamma P$; in that case:

(A9a) $P = \frac{1}{1+\gamma} T_A$

(A9b) $\pi = \lambda_B = \frac{2\alpha_B}{1+\gamma} T_A + 2\alpha_B T_B = 2\alpha_B R_B$

(A9c) $\lambda_A = \frac{2\alpha_A \gamma^2 + 2\alpha_B}{(1+\gamma)^2} T_A + \frac{2\alpha_B}{1+\gamma} T_B$

(A9d) $\lambda_C = \frac{2\alpha_A \gamma - 2\alpha_B}{(1+\gamma)^2} T_A - \frac{2\alpha_B}{1+\gamma} T_B$

(A9e) $R_A = \frac{\gamma}{1+\gamma} T_A$

(A9f) $R_B = \frac{1}{1+\gamma} T_A + T_B$

With sellers' liability, the problem looks like:

(A10) $\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ s.t. $R_A + P \geq T_A; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P$ s.t. $R_B - (1+\mu) P \geq T_B$

with $\mu \geq 0$.

The first order conditions are:

(A11a) $2\alpha_A R_A - \lambda_A = 0$

(A11b) $\pi - \lambda_A = 0$

(A11c) $R_A + P - T_A = 0$
(A11d) $2\alpha_B R_B - \lambda_B = 0$
(A11e) $-\pi + \lambda_B(1+\mu) = 0$
(A11f) $R_B - (1+\mu)P - T_B = 0$
Total emissions fall by μP. This solves as:
(A12a) $P = \frac{\alpha_A}{\alpha_A + \alpha_B(1+\mu)^2} T_A - \frac{\alpha_B(1+\mu)}{\alpha_A + \alpha_B(1+\mu)^2} T_B$
(A12b) $\pi = \lambda_A = \frac{2\alpha_A\alpha_B(1+\mu)^2}{\alpha_A + \alpha_B(1+\mu)^2} T_A + \frac{2\alpha_A\alpha_B(1+\mu)}{\alpha_A + \alpha_B(1+\mu)^2} T_B$
(A12c) $\lambda_B = \frac{2\alpha_A\alpha_B(1+\mu)}{\alpha_A + \alpha_B(1+\mu)^2} T_A + \frac{2\alpha_A\alpha_B}{\alpha_A + \alpha_B(1+\mu)^2} T_B$
(A12d) $R_A = \frac{\alpha_B(1+\mu)^2}{\alpha_A + \alpha_B(1+\mu)^2} T_A + \frac{\alpha_B(1+\mu)}{\alpha_A + \alpha_B(1+\mu)^2} T_B$
(A12e) $R_B = \frac{\alpha_A(1+\mu)}{\alpha_A + \alpha_B(1+\mu)^2} T_A + \frac{\alpha_A}{\alpha_A + \alpha_B(1+\mu)^2} T_B$
If μ=0, (A12) returns to (4).

Under buyers' liability and a tariff, the problem is:
(A13) $\min_{R_A} C_A = \alpha_A R_A^2 + t\pi P$ s.t. $R_A + (1-p)P \geq T_A; \min_{R_B} C_B = \alpha_B R_B{}^2 - \pi P$ s.t. $R_B - P \geq T_B$
with $0 \leq p \leq 1$ and $t \geq 1$.

The first order conditions of are:
(A14a) $2\alpha_A R_A - \lambda_A = 0$
(A14b) $t\pi - \lambda_A(1-p) = 0$
(A14c) $R_A + (1-p)P - T_A = 0$
(A14d) $2\alpha_B R_B - \lambda_B = 0$
(A14e) $-\pi + \lambda_B = 0$
(A14f) $R_B - P - T_B = 0$
Total emissions fall by pP. This solves as:
(A15a) $P = \frac{\alpha_A(1-p)}{\alpha_A(1-p)^2 + \alpha_B t} T_A - \frac{\alpha_B t}{\alpha_A(1-p)^2 + \alpha_B t} T_B$
(A15b) $\pi = \lambda_B = \frac{2\alpha_A\alpha_B(1-p)}{\alpha_A(1-p)^2 + \alpha_B t} T_A + \frac{2\alpha_A\alpha_B(1-p)^2}{\alpha_A(1-p)^2 + \alpha_B t} T_B$
(A15c) $\lambda_A = \frac{2\alpha_A\alpha_B t}{\alpha_A(1-p)^2 + \alpha_B t} T_A + \frac{2\alpha_A\alpha_B t(1-p)}{\alpha_A(1-p)^2 + \alpha_B t} T_B$
(A15d) $R_A = \frac{\alpha_B t}{\alpha_A(1-p)^2 + \alpha_B t} T_A + \frac{\alpha_B t(1-p)}{\alpha_A(1-p)^2 + \alpha_B t} T_B$
(A15e) $R_B = \frac{\alpha_A(1-p)}{\alpha_A(1-p)^2 + \alpha_B t} T_A + \frac{\alpha_A(1-p)^2}{\alpha_A(1-p)^2 + \alpha_B t} T_B$
If t=1, (A15) returns to (A3), with (1-p)=d. If p=0, (A15) returns to (A6). If t=1 and p=0, (A15) returns to (4).

Under buyers' liability and an import quota, the problem looks like:

(A16)

$$\min_{R_A} C_A = \alpha_A R_A^2 + \pi P \text{ s.t. } R_A + (1-p)P \geq T_A \text{ and } R_A \geq \gamma P; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P \text{ s.t. } R_B - P \geq T_B$$

with 0≤ $p \leq 1$ and γ> 0.

The first order conditions are:
(A17a) $2\alpha_A R_A - \lambda_A - \lambda_C = 0$
(A17b) $\pi - \lambda_A(1-p) + \lambda_C\gamma = 0$
(A17c) $R_A + (1-p)P - T_A = 0$
(A17d) $R_A - \gamma P = 0$
(A17e) $2\alpha_B R_B - \lambda_B = 0$
(A17f) $-\pi + \lambda_B = 0$
(A17g) $R_B - P - T_B = 0$

Total emissions stay the same. This solves as:
(A18a) $P = \frac{1}{(1-p)+\gamma} T_A$
(A18b) $\pi = \lambda_B = \frac{2\alpha_B}{(1-p)+\gamma} T_A + 2\alpha_B T_B = 2\alpha_B R_B$
(A18c) $\lambda_A = \frac{2\alpha_A\gamma^2 + 2\alpha_B}{((1-p)+\gamma)^2} T_A + \frac{2\alpha_B}{(1-p)+\gamma} T_B$
(A18d) $\lambda_C = \frac{2\alpha_A\gamma(1-p) - 2\alpha_B}{((1-p)+\gamma)^2} T_A - \frac{2\alpha_B}{(1-p)+\gamma} T_B$
(A18e) $R_A = \frac{\gamma}{(1-p)+\gamma} T_A$
(A18f) $R_B = \frac{1}{(1-p)+\gamma} T_A + T_B$
if $p = 0$, (A18) returns to (A9).

Under seller's liability in combination with a discount, the problem looks like:
(A19) $\min_{R_A} C_A = \alpha_A R_A^2 + \pi P \text{ s.t. } R_A + dP \geq T_A; \min_{R_B} C_B = \alpha_B {R_B}^2 - \pi P \text{ s.t. } R_B - (1+\mu)P \geq T_B$
with $\mu \geq$0 and 0≤ d ≤1.

The first order conditions are:
(A20a) $2\alpha_A R_A - \lambda_A = 0$
(A20b) $\pi - \lambda_A d = 0$
(A20c) $R_A + dP - T_A = 0$
(A20d) $2\alpha_B R_B - \lambda_B = 0$
(A20e) $-\pi + \lambda_B(1+\mu) = 0$
(A20f) $R_B - (1+\mu)P - T_B = 0$
Total emissions fall by (1+μ-d)P. This solves as:

(A21a) $P=\frac{\alpha_A d}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_A-\frac{\alpha_B(1+\mu)}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_B$

(A21b) $\pi=\frac{2\alpha_A\alpha_B d(1+\mu)^2}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B d^2(1+\mu)}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_B$

(A21c) $\lambda_A=\frac{2\alpha_A\alpha_B(1+\mu)^2}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B d(1+\mu)}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_B$

(A21d) $\lambda_B=\frac{2\alpha_A\alpha_B d(1+\mu)}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B d^2}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_B$

(A21e) $R_A=\frac{\alpha_B(1+\mu)^2}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_A+\frac{\alpha_B d(1+\mu)}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_B$

(A21f) $R_B=\frac{\alpha_A d(1+\mu)}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_A+\frac{\alpha_A d^2}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_B$

If μ=0, (A21) returns to (A3). If d=0, (A21) returns to (A12). If μ=d=0, (A21) returns to (4).

Under seller's liability in combination with a tariff, the problem looks like:

(A22) $\min_{R_A} C_A=\alpha_A R_A^2+t\pi P$ s.t. $R_A+P\geq T_A$; $\min_{R_B} C_B=\alpha_B R_B{}^2-\pi P$ s.t. $R_B-(1+\mu)P\geq T_B$

with $\mu\geq0$ and $t\geq1$. The first order conditions are:

(A23a) $2\alpha_A R_A-\lambda_A=0$

(A23b) $t\pi-\lambda_A=0$

(A23c) $R_A+P-T_A=0$

(A23d) $2\alpha_B R_B-\lambda_B=0$

(A23e) $-\pi+\lambda_B(1+\mu)=0$

(A23f) $R_B-(1+\mu)P-T_B=0$

Total emissions fall by μP. This solves as:

(A24a) $P=\frac{\alpha_A}{\alpha_A+\alpha_B t(1+\mu)^2}T_A-\frac{\alpha_B t(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$

(A24b) $\pi=\frac{2\alpha_A\alpha_B(1+\mu)^2}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$

(A24c) $\lambda_A=\frac{2\alpha_A\alpha_B t(1+\mu)^2}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B t(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$

(A24d) $\lambda_B=\frac{2\alpha_A\alpha_B(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$

(A24e) $R_A=\frac{\alpha_B t(1+\mu)^2}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{\alpha_B t(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$

(A24f) $R_B=\frac{\alpha_A(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{\alpha_A}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$

If μ=0, (A24) returns to (A6). If t=1, (A24) returns to (A12). If μ=0 and t=1, (A24) returns to (4).

Under seller's liability in combination with an import quota, the problem looks like:

(A25)

$$\min_{R_A} C_A = \alpha_A R_A^2 + \pi P \text{ s.t. } R_A + P \geq T_A \text{ and } R_A \geq \gamma P; \min_{R_B} C_B = \alpha_B R_B^2 - \pi P \text{ s.t. } R_B - (1+\mu)P \geq T_B$$

with $\mu \geq 0$ and $\gamma > 0$.

The first order conditions are:

(A26a) $2\alpha_A R_A - \lambda_A - \lambda_C = 0$

(A26b) $\pi - \lambda_A + \lambda_C \gamma = 0$

(A26c) $R_A + P - T_A = 0$

(A26d) $R_A - \gamma P = 0$

(A26e) $2\alpha_B R_B - \lambda_B = 0$

(A26f) $-\pi + (1+\mu)\lambda_B = 0$

(A26g) $R_B - (1+\mu)P - T_B = 0$

Total emissions stay the same. This solves as:

(A27a) $P = \frac{1}{1+\gamma} T_A$

(A27b) $\pi = \frac{2\alpha_B (1+\mu)^2}{1+\gamma} T_A + 2\alpha_B (1+\mu) T_B$

(A27c) $\lambda_B = \frac{2\alpha_B (1+\mu)}{1+\gamma} T_A + 2\alpha_B T_B = 2\alpha_B R_B$

(A27d) $\lambda_A = \frac{2\alpha_A \gamma^2 + 2\alpha_B (1+\mu)^2}{(1+\gamma)^2} T_A + \frac{2\alpha_B (1+\mu)}{1+\gamma} T_B$

(A27e) $\lambda_C = \frac{2\alpha_A \gamma - 2\alpha_B (1+\mu)^2}{(1+\gamma)^2} T_A - \frac{2\alpha_B (1+\mu)}{1+\gamma} T_B$

(A27f) $R_A = \frac{\gamma}{1+\gamma} T_A$

(A27g) $R_B = \frac{1+\mu}{1+\gamma} T_A + T_B$

If $\mu = 0$, (A27) returns to (A9).

Table 1. The shadow prices of both countries without trade, with free trade, and with 11 forms of restricted trade.

	Shadow price, Country A	Shadow price, Country B	Ratio
No Trade	$2\alpha_A T_A$	$2\alpha_B T_B$	$\frac{2\alpha_A T_A}{2\alpha_B T_B}$
Free trade	$\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B}T_A+\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B}T_B$	$\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B}T_A+\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B}T_B$	$\frac{1}{1}$
Discount	$\frac{2\alpha_A\alpha_B}{\alpha_A d^2+\alpha_B}T_A+\frac{2\alpha_A\alpha_B d}{\alpha_A d^2+\alpha_B}T_B$	$\frac{2\alpha_A\alpha_B d}{\alpha_A d^2+\alpha_B}T_A+\frac{2\alpha_A\alpha_B d^2}{\alpha_A d^2+\alpha_B}T_B$	$\frac{1}{d}$
Tariff	$\frac{2\alpha_A\alpha_B t}{\alpha_A+\alpha_B t}T_A+\frac{2\alpha_A\alpha_B t}{\alpha_A+\alpha_B t}T_B$	$\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B t}T_A+\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B t}T_B$	$\frac{t}{1}$
Import Quota	$\frac{2\alpha_A\gamma^2+2\alpha_B}{(1+\gamma)^2}T_A+\frac{2\alpha_B}{1+\gamma}T_B$	$\frac{2\alpha_B}{1+\gamma}T_A+2\alpha_B T_B=2\alpha_B R_B$	$\frac{\left(\alpha_A\gamma^2+\alpha_B\right)T_A+\alpha_B\left(1+\gamma\right)T_B}{\alpha_B\left(1+\gamma\right)T_A+\alpha_B(1+\gamma)^2 T_B}$
Buyers' Liability	$\frac{2\alpha_A\alpha_B}{\alpha_A(1-p)^2+\alpha_B}T_A+\frac{2\alpha_A\alpha_B(1-p)}{\alpha_A(1-p)^2+\alpha_B}T_B$	$\frac{2\alpha_A\alpha_B(1-p)}{\alpha_A(1-p)^2+\alpha_B}T_A+\frac{2\alpha_A\alpha_B(1-p)^2}{\alpha_A(1-p)^2+\alpha_B}T_B$	$\frac{1}{1-p}$
Sellers' Liability	$\frac{2\alpha_A\alpha_B(1+\mu)^2}{\alpha_A+\alpha_B(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B(1+\mu)}{\alpha_A+\alpha_B(1+\mu)^2}T_B$	$\frac{2\alpha_A\alpha_B(1+\mu)}{\alpha_A+\alpha_B(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B(1+\mu)^2}T_B$	$\frac{1+\mu}{1}$
Buyers' Liability and Discount	$\frac{2\alpha_A\alpha_B}{\alpha_A d^2(1-p)^2+\alpha_B}T_A+\frac{2\alpha_A\alpha_B d(1-p)}{\alpha_A d^2(1-p)^2+\alpha_B}T_B$	$\frac{2\alpha_A\alpha_B d(1-p)}{\alpha_A d^2(1-p)^2+\alpha_B}T_A+\frac{2\alpha_A\alpha_B d^2(1-p)^2}{\alpha_A d^2(1-p)^2+\alpha_B}T_B$	$\frac{1}{d(1-p)}$
Buyers' Liability and Tariff	$\frac{2\alpha_A\alpha_B t}{\alpha_A(1-p)^2+\alpha_B t}T_A+\frac{2\alpha_A\alpha_B(1-p)t}{\alpha_A(1-p)^2+\alpha_B t}T_B$	$\frac{2\alpha_A\alpha_B(1-p)}{\alpha_A(1-p)^2+\alpha_B t}T_A+\frac{2\alpha_A\alpha_B(1-p)^2}{\alpha_A(1-p)^2+\alpha_B t}T_B$	$\frac{t}{1-p}$
Buyers' Liability and Quota	$\frac{2\alpha_A\gamma^2+2\alpha_B}{((1-p)+\gamma)^2}T_A+\frac{2\alpha_B}{(1-p)+\gamma}T_B$	$\frac{2\alpha_B}{(1-p)+\gamma}T_A+2\alpha_B T_B=2\alpha_B R_B$	$\frac{\left(\alpha_A\gamma^2+\alpha_B\right)T_A+\alpha_B\left(1+\gamma-p\right)T_B}{\alpha_B\left(1+\gamma-p\right)T_A+\alpha_B(1+\gamma-p)^2 T_B}$
Sellers' Liability and Discount	$\frac{2\alpha_A\alpha_B(1+\mu)^2}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B d(1+\mu)}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_B$	$\frac{2\alpha_A\alpha_B d(1+\mu)}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B d^2}{\alpha_A d^2+\alpha_B(1+\mu)^2}T_B$	$\frac{1+\mu}{d}$
Sellers' Liability and Tariff	$\frac{2\alpha_A\alpha_B t(1+\mu)^2}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B t(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$	$\frac{2\alpha_A\alpha_B(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$	$\frac{t(1+\mu)}{1}$
Sellers' Liability and Quota	$\frac{2\alpha_A\gamma^2+2\alpha_B(1+\mu)^2}{(1+\gamma)^2}T_A+\frac{2\alpha_B(1+\mu)}{1+\gamma}T_B$	$\frac{2\alpha_B(1+\mu)}{1+\gamma}T_A+2\alpha_B T_B=2\alpha_B R_B$	$\frac{\left(\alpha_A\gamma^2+\alpha_B(1+\mu)^2\right)T_A+\alpha_B(1+\gamma)(1+\mu)T_B}{\alpha_B(1+\gamma)\left((1+\mu)T_A+(1+\gamma)T_B\right)}$

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