ON NATIONAL AND INTERNATIONAL TRADE IN GREENHOUSE GAS EMISSION PERMITS

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Working Paper FNU-11 (revised)

Abstract

Economic analyses of emission permit trading have mainly looked into the cost effectiveness and cost saving potential of international permit trading compared to a pure national trading system. Little attention has been drawn to the environmental effectiveness of international trade in greenhouse gas emission permits. Less environmental ambitiousness caused by relatively low emission reduction targets in some countries might lower the permit price on the international market, but might also reduce environmental effectiveness.

This paper considers the question under what conditions domestic markets of emission permits would and should merge to become an international market when environmental integrity has to be preserved and how environmental and cost effectiveness could be combined. In a two-country model 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. An import quota would also stress the idea of supplementary of the flexible mechanism as it increases the share of emissions reduced domestically. 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 effectiveness, environmental integrity, environmental policy, liability and compliance

JEL Classification: Q25, Q28

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 legally binding emission reduction targets and international flexibility mechanisms, including trade in emission permits. However, progress in international negotiations is slow, and failure is not excluded. Some countries may be impatient, and regulate carbon dioxide emissions with a domestic market for emission permits. Denmark and the UK indeed have done so already. Or, if the international negotiations collapse, some countries may want to reduce emissions unilaterally, but reap the benefits of international flexibility mechanisms nonetheless. This paper investigates the question whether international trade in emission permits is possible without a multilateral treaty on emission reduction targets or even a multilateral treaty on regulating international trade. The answer to both questions is affirmative, contrary to the apparent belief of at least some of the negotiators on and analysts of climate policy. Although this paper is phrased in terms of climate change, its results hold for other transboundary externalities as well.

In this paper, there is trade between countries with different beliefs about the seriousness of climate change. We analyze the possibilities of regulating the international market with price and quantity instruments in a stylized two-country model. We find that it is in both countries interests to form an international market and it may even be beneficial to the environment. Our two-country model can easily be generalized to many countries, and our approach might also be useful to investigate emissions trade between the U.S. and countries that ratified the KP, between the developing countries and the Annex B countries, and even between Annex B countries in a future commitment period. The policy instruments discussed in this paper might be used by countries who want to do more than other countries or than agreed on internationally.[1]

There is little, if any, literature on this subject. The original literature on tradable permits is all framed in a domestic context. The literature on internationally traded permits almost unanimously assumes that there is an international agreement on at least the permit allocation. Boom (2001), an exception, examines the effects on abatement commitments, total emissions

[1] See e.g. Babiker *et al.* (2002). Andresen *et al.* (2002) investigate Norway as an early test case for the feasibility of ambitious climate agreements.

and welfare of international emissions trading. Bohm (1992) and Helm (2000) also investigate the (re)distribution effects of trade, and thus implicitly the desire of countries to adopt different emission reduction targets with trade than without. However, these papers do not consider domestic or institutional regulation of the international market. Bradford (2001) proposes a "no-cap but trade" system in which countries voluntarily contribute money to a global organization, which subsequently purchases emission reduction where that is cheapest. We share Bradford's lack of an international agreement on targets, and international cost-effectiveness, but our mechanism is quite different.

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 expands the analysis to liability issues, and examines the consequences for a bi-national market in emission permits. Section 6 concludes.

2. The case of two domestic emissions markets

Let us consider two countries, each committed to reducing their emissions of greenhouse gases.[2] Let us assume that the costs of emission abatement in one country are independent of emission reduction costs in the other country.[3] 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. α is a parameter. The solution to (1) is that $R_A=T_A$ and $R_B=T_B$. The marginal costs are $2\alpha_A T_A$ and $2\alpha_B T_B$, respectively.

Now let us introduce trade in emission permits. Without loss of generality, we assume that Country A imports permits from Country B, that is $\alpha_A>\alpha_B$:

(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.

[2] For simplicity, we discuss the case of only one greenhouse gas in the following sections, but the analysis could be easily extended to more.
[3] See Kemfert *et al.* (2001) for alternative assumptions.

The first order conditions of (2) are:

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

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

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

(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[4]) 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.[5] See Table I.

As expected, 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:

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

[5] 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.

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

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.

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. With trade, for both countries, a lower target in the other country implies lower costs for both countries, as it decreases the permit price and increases the amount of traded permits.

3. Domestic regulation of a bi-national market

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.[6]

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.

3.1 Quantity instruments: Carbon discount and import quota

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.

[6] 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).

With a carbon discount, the problem looks like:

(6) $\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ 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 $0 \leq d \leq 1$.[7] For given emission reduction targets, total emissions fall by (1-*d*)*P*. The shadow prices of both countries are given in Table I, 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 ratio of shadow prices changes to $1/d$, so that this ratio can in principle also reflect the ratio of the marginal benefits[8] 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.

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. 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 and to stress the supplementary requirements.[9] With such an import quota the problem looks as follows:

(7) $\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ 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 $\gamma > 0$.[10] 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 I, as is their ratio.

Introducing an import quota γ has the same effects on the costs as a carbon discount has. Compared to a situation of free trade it reduces the shadow price in the selling country and raises it in the buying country. 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 and more so if B's target is weak. This is not generally true – it depends on both

[7] The first-order conditions and the solution are given in the appendix.
[8] That is, the benefits of reduced climate change.
[9] See Baron *et al.* (1999), Woerdman (2001) and Westskog (forthcoming).
[10] The first-order conditions and the solution are given in the appendix.

countries emission reduction targets together with the extent of A's import restrictions. If trade is not affected by the constraint, that is A reduces more than required domestically, we have a free trade situation.

3.2 Price instrument: Tariff

Besides a quantity instrument, the buying country can also introduce a price instrument, like a tariff. A major difference with the quantity instruments 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. With a tariff, the problem looks as follows:[11]

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

with $t \geq 1$. Total emissions are not affected by a tariff. The shadow prices of both countries are given in Table I, 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 quantity instruments, 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.

3.3 Comparison of the different instruments

In this section, we use two numerical simulations to compare total and marginal costs for both countries to illustrate the differences and equalities of the different instruments with respect to costs. The relationship between discount and tariff (with t=1/d) to the quota follows from (A6). See also Table I where the ratios of the shadow prices are calculated.

Figure 1 displays total costs for both countries as a function of the discount, the tariff and the import quota. 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, quota or tariff is used for regulation. 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 because of the

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

revenue of the tariff. 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, but 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.

A tariff is always more expensive to Country B than a discount. A tariff reaps some of B's producer surplus and transfers it to A. 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 1 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[12] if its emission reduction target is low or negative.[13] 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 ($d < 1$).

[12] See the lower left side of Figure 1.

[13] Low target stands here for a situation where Country B would have no costs but net benefits with free trade, that is trading hot air.

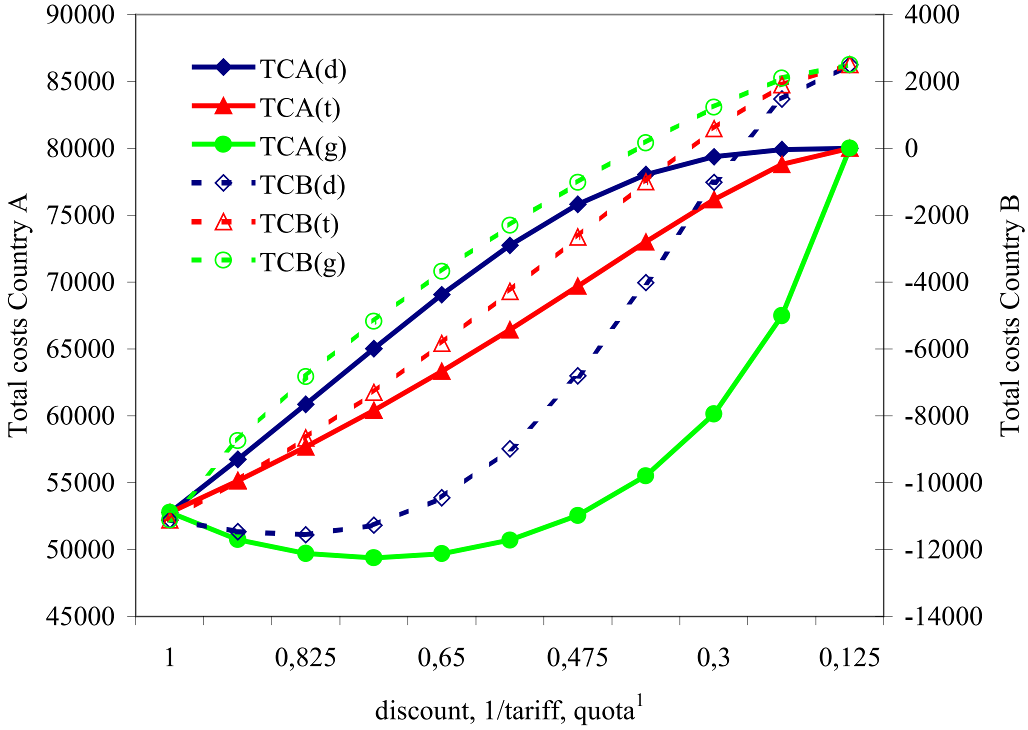

Figure 1. The total costs of Country A (left axis) and Country B (right axis) as a function of the discount, tariff and quota. The point on the far left corresponds to the situation of free trade, the far right point to the situation of no trade. The target of Country A is 200; B's target is 50; α_A=2; α_B=1. [1]The equation for the relation between quota and discount or tariff follows from (A6). See also Table I. For R_A=200 and R_B=50; γ varies from 0.7 to 9.

Figure 2 shows the shadow prices of both countries as a function of the discount, the tariff and the import quota. The figure confirms that trade increases the shadow price of emission control in Country B, and decreases 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.[14] A tariff and a quota make B's shadow price fall faster than does a discount; this is independent of parameter choice. 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.

[14] This can be seen by solving P=0 for d and t in Equations (A3a) and (A9a), respectively, and substituting the results in Equations (A3b-c) and (A9b-c), respectively. For γ, this can be directly seen from (A6a).

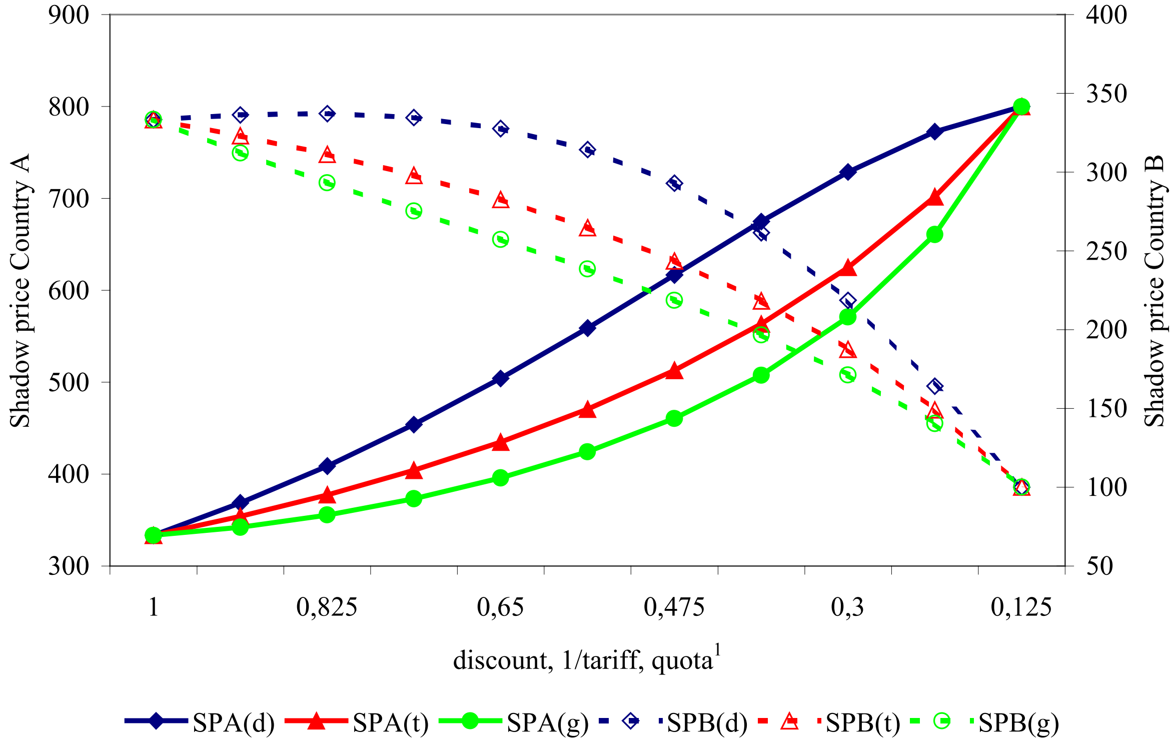

Figure 2. The shadow prices of Country A (left axis) and Country B (right axis) as a function of the discount, tariff and import quota. The point on the far left corresponds to the situation of free trade, and the far right to the situation of no trade. The target of Country A is 200; B's target is 50; α_A=2; α_B=1. [1]The equation for the relation between quota and discount or tariff follows from (A6). See also Table I. For R_A=200 and R_B=50; γ varies from 0.7 to 9.

4. Environmental integrity

One of the reasons why Country A would regulate trade is to prevent Country B from issuing more and more permits and perhaps influence Country B to adopt a more ambitious target. 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.[15] 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 3. We assume that if Country B lowers its target, Country A increases the discount so that total emissions stay constant[16], 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.

[15] 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.
[16] The equation for this follows straightforwardly from (A3).

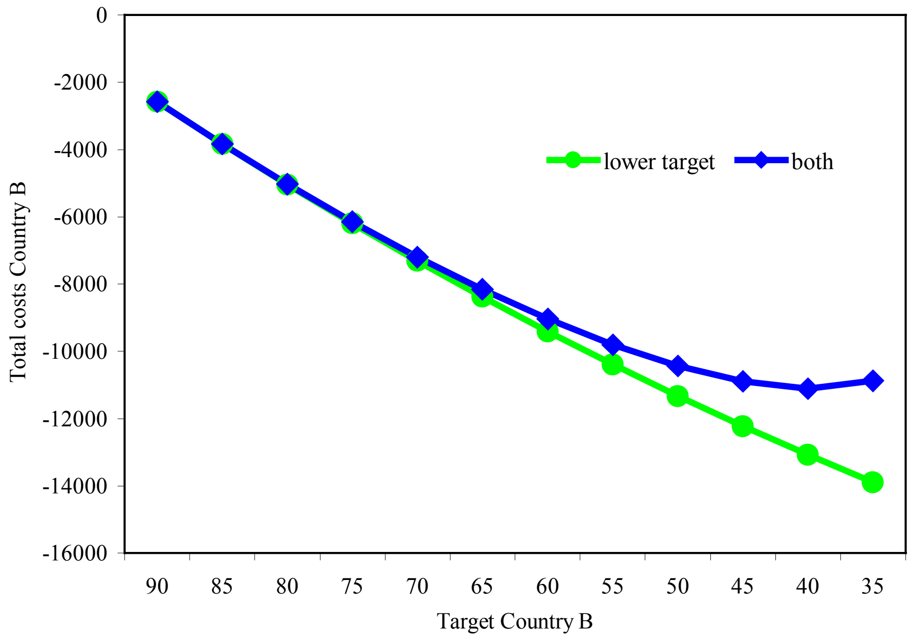

Figure 3. The total costs of Country B for three cases. In the first case ("lower target"), the discount is kept constant (at 0.95 when B reduces the target first from 90 to 85) and B's target is varied (from 90 down to 35). In the second case ("both"), both the discount (from 1.00 to 0.50) and B's target are varied and exactly offset each other with regard to total emissions ($R_A+R_B=290$). The target of Country A is 200; $\alpha_A=2$; $\alpha_B=1$.

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" at first sight, but they might support A's effort to prevent country B from choosing a too low emission reduction target. Country A might use those instruments as an deterrent. Therefore, we turn our attention to tariff, discount and quota as a means for Country A to regulated the amount of imported permits.[17]

Figure 4 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 exactly offsets B's lower target.[18] 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. Using a discount would increase the amount of emissions reduced internationally significantly, but at A's expense.

[17] The equation for this follows from (A3), (A6) and (A9).
[18] However, if we would have chosen in our numerical example a lower target for Country B, it would have been sufficient for Country A to hold the amount of imported permits constant.

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 4, 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.

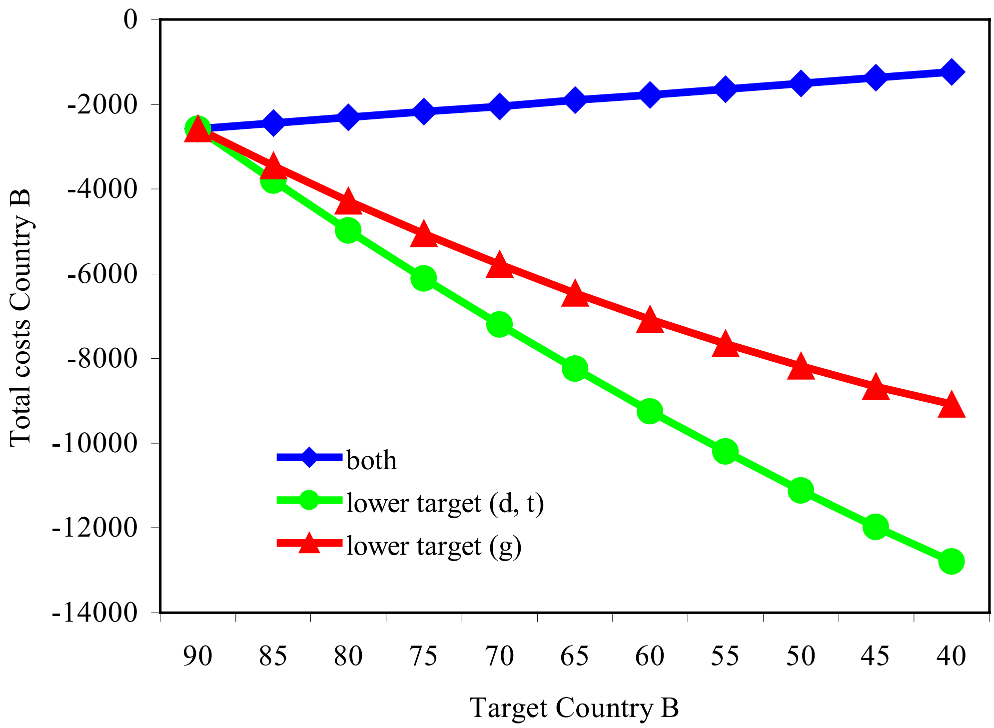

Figure 4. Total costs of Country B for three cases. In the first case ("lower target"), tariff, discount and quota are kept constant and B's target is varied (from 90 to 40). In the second case ("both"), both the tariff, the discount respectively the quota (tariff from 1 to 3.15, discount from 1 to 0.25, quota from 0.94 to 2.75) and B's target are varied and exactly offset each other with regard to the amount of traded permits. P decreases from 103 to 53 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.

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.[19] 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.[20] 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 market. In this section, we discuss the two main principles, sellers' and buyers' liability.

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.

[19] At COP-7 in Marrakech in November 2001 a compliance penalty including suspension of eligibility to use the flexibility mechanism and a deduction of any first-period shortfall from the allocation for the second commitment period was agreed; UNFCCC (2001). However, the legal text on compliance was delayed after the Protocol has entered into force.

[20] A survey of proposals is presented in Baron (1999) and Nordhaus *et al.* (2000).

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.[21] 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.[22] 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:

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

with $0 \leq p \leq 1$.[23] 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 I 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. 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.

The problem then looks like:

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

[21] 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.
[22] 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.
[23] The first-order conditions and solution are given in the appendix.

with $\mu \geq 0$.[24] Total emissions fall by μP. Table I 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.

In the following two sections, we use numerical simulations to first compare both liability principles and then include the regulatory instruments into the analysis. The equations for the relation of costs from discount, tariff and quota under sellers' or buyers' liability are taken from Table I.

5.1 Comparison of buyers' and sellers' liability

Figure 5 compares the gains of trade under sellers' and buyers' liability to a situation of free trade.[25] 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 buyers' 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.

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

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

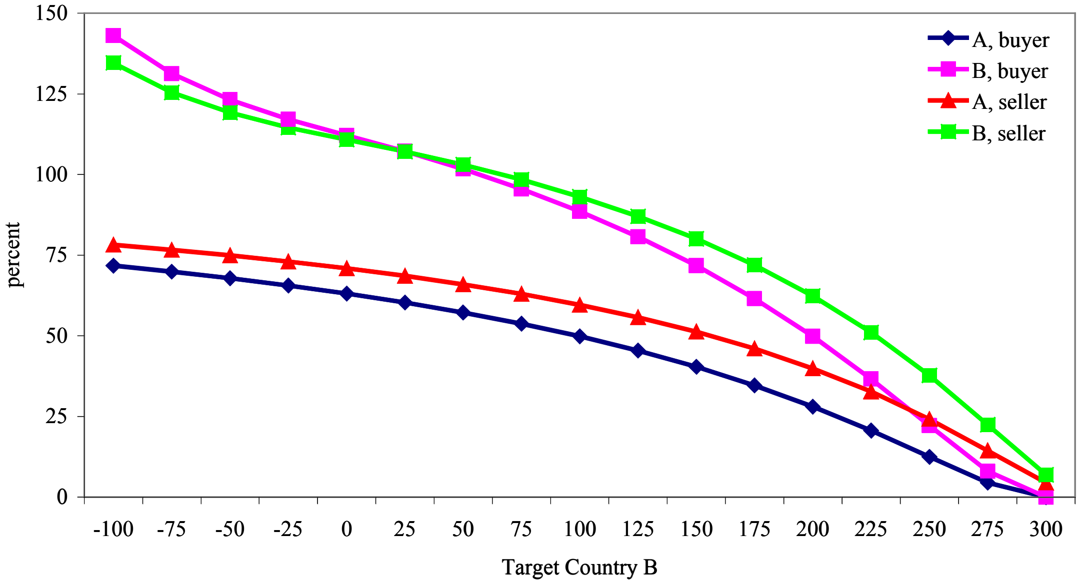

Figure 5. Relative gains of trade for Country A and Country B under sellers' or buyers' liability as a function of the tightness of the market; the target of Country A is always 200, B's target varies. The gains of trade with liability as a percentage of the gains without liability are displayed. α_A=2; α_B=1; p=μ=0.25.

The effect on the marginal costs of Country A is not surprising. See Figure 6. 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.

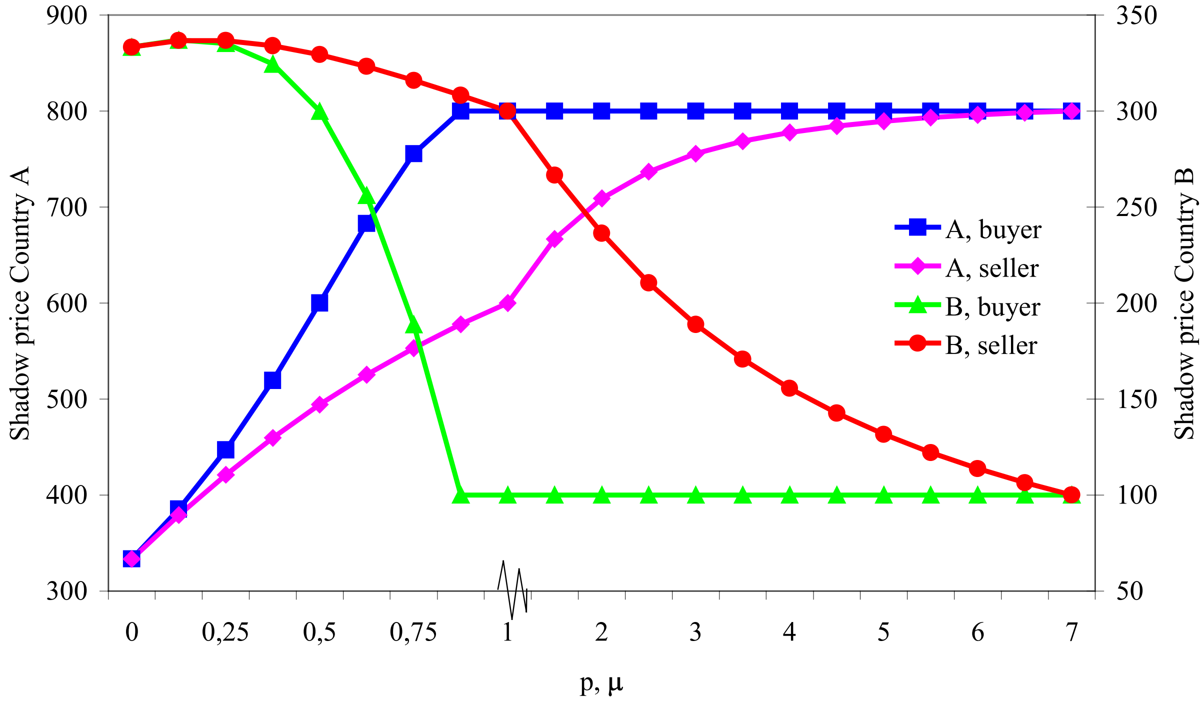

Figure 6. The shadow prices of Country A (left axis) and Country B (right axis) under sellers' and buyers' liability as a function of the chance of non-compliance. The point on the far left corresponds to the situation of free trade, and the far right point to the situation of no trade. The target of 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) $$P = 0 \Leftrightarrow (1-p)\alpha_A T_A = \alpha_B T_B \Leftrightarrow p = 1 - \frac{\alpha_B T_B}{\alpha_A T_A}$$

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.

5.2 Compliance, liability and environmental integrity

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.[26] 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 I 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 7 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 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.

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

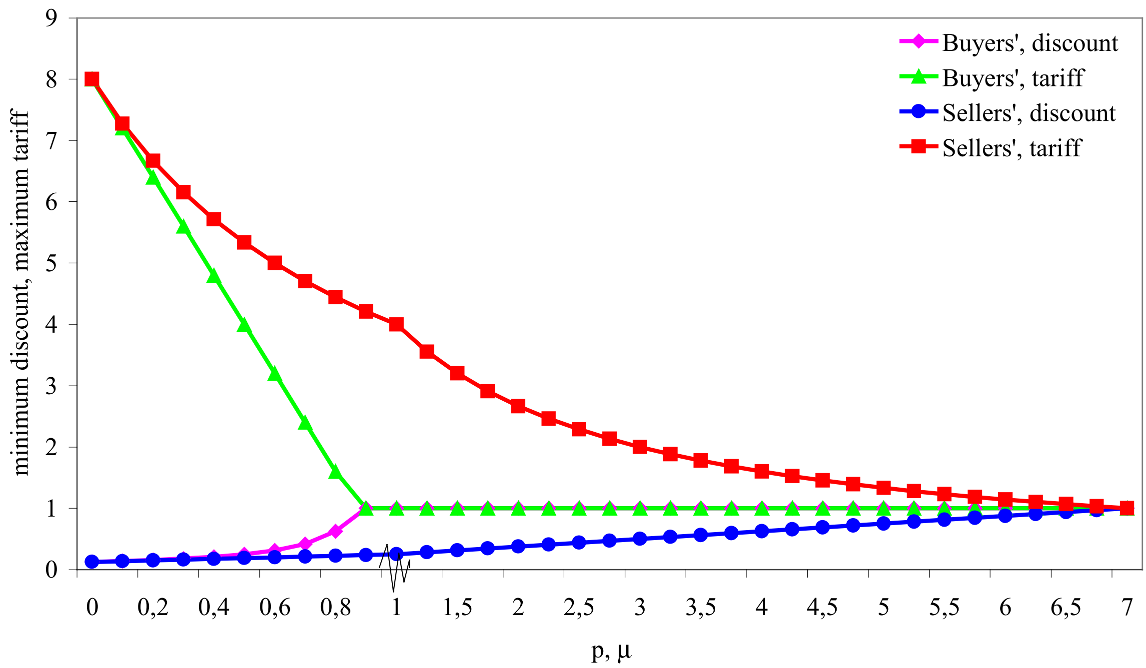

Figure 7. The minimum discount (the *d* for which *P*=0) and the maximum tariff (the *t* for which *P*=0) as a function of the uncertainty (*p* and *μ*, respectively) underlying buyers' liability and sellers' liability. The target of Country A is 200; B's target is 50; α_A=2; α_B=1.

An import quota would not stop trade, unless the restriction is that all emission permits are domestic, that is, $\gamma \to \infty$ in (A15) and (A24).

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. It seems less likely to achieve both cost effectiveness and environmental effectiveness, but there is a potential to improve environmental effectiveness at lowest cost possible.

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 encourage the selling country to accept a stricter target they intended or 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. An import quota would stress the idea of supplementary of international emission permit trading as it increases the share of emissions reduced domestically. Furthermore, it might be easier to implement than e.g. a tariff, as there are continuous debates on imposing tariffs for whatever reasons.

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. 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. Secondly, the choice of domestic emission standards should be made explicit. Thirdly, the domestic market of emission permits needs to be modeled. Fourthly, the analysis should be extended to multiple greenhouse gases. This is straightforward if both countries use the same exchange rates between gases, but introduces additional friction if not. These tasks are deferred to future research.

Acknowledgements
We thank Roberto Roson and Andries Nentjes for helpful comments and discussion. A version of this paper was presented at the FEEM/CATEP Workshop on Trading Scales: Linking Industry, Local/Regional, National and International Emissions Trading Schemes, Venice, December 3-4, 2001. The US National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914), the Hamburg Ministry for Science and Research and the Michael Otto Foundation provided welcome financial support. All errors and opinions are ours.

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 an import quota, the problem looks like:

(A4) $\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ 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:

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

(A5b) $\pi - \lambda_A + \lambda_C \gamma = 0$

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

(A5d) $R_A - \gamma P = 0$

(A5e) $2\alpha_B R_B - \lambda_B = 0$

(A5f) $-\pi + \lambda_B = 0$

(A5g) $R_B - P - T_B = 0$

Total emissions stay the same.

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

(A6a) $P = \frac{1}{1+\gamma} T_A$

(A6b) $\pi = \lambda_B = \frac{2\alpha_B}{1+\gamma} T_A + 2\alpha_B T_B = 2\alpha_B R_B$

(A6c) $\lambda_A = \frac{2\alpha_A \gamma^2 + 2\alpha_B}{(1+\gamma)^2} T_A + \frac{2\alpha_B}{1+\gamma} T_B$

(A6d) $\lambda_C = \frac{2\alpha_A \gamma - 2\alpha_B}{(1+\gamma)^2} T_A - \frac{2\alpha_B}{1+\gamma} T_B$

(A6e) $R_A = \frac{\gamma}{1+\gamma} T_A$

(A6f) $R_B = \frac{1}{1+\gamma} T_A + T_B$

With a tariff, the problem looks as follows:

(A7) $\min_{R_A} C_A = \alpha_A R_A^2 + t\pi P$ 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:

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

(A8b) $t\pi - \lambda_A = 0$

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

(A8d) $2\alpha_B R_B - \lambda_B = 0$

(A8e) $-\pi + \lambda_B = 0$

(A8f) $R_B - P - T_B = 0$

Total emissions stay the same.

This solves as:

(A9a) $P = \frac{\alpha_A}{\alpha_A + \alpha_B t} T_A - \frac{\alpha_B t}{\alpha_A + \alpha_B t} T_B$

(A9b) $\pi = \lambda_B = \frac{2\alpha_A \alpha_B}{\alpha_A + \alpha_B t} T_A + \frac{2\alpha_A \alpha_B}{\alpha_A + \alpha_B t} T_B$

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

(A9d) $R_A = \frac{\alpha_B t}{\alpha_A + \alpha_B t} T_A + \frac{\alpha_B t}{\alpha_A + \alpha_B t} T_B$

(A9e) $R_B = \frac{\alpha_A}{\alpha_A + \alpha_B t} T_A + \frac{\alpha_A}{\alpha_A + \alpha_B t} T_B$

If t=1, (A9) returns to (4).

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 an import quota, the problem looks like:

(A13)

$\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ s.t. $R_A + (1-p)P \geq T_A$ 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 $0 \leq p \leq 1$ and $\gamma > 0$.

The first order conditions are:

(A14a) $2\alpha_A R_A - \lambda_A - \lambda_C = 0$

(A14b) $\pi - \lambda_A(1-p) + \lambda_C \gamma = 0$

(A14c) $R_A + (1-p)P - T_A = 0$

(A14d) $R_A - \gamma P = 0$

(A14e) $2\alpha_B R_B - \lambda_B = 0$

(A14f) $-\pi + \lambda_B = 0$

(A14g) $R_B - P - T_B = 0$

Total emissions stay the same.

This solves as:

(A15a) $P = \frac{1}{(1-p)+\gamma} T_A$

(A15b) $\pi = \lambda_B = \frac{2\alpha_B}{(1-p)+\gamma} T_A + 2\alpha_B T_B = 2\alpha_B R_B$

(A15c) $\lambda_A = \frac{2\alpha_A \gamma^2 + 2\alpha_B}{((1-p)+\gamma)^2} T_A + \frac{2\alpha_B}{(1-p)+\gamma} T_B$

(A15d) $\lambda_C = \frac{2\alpha_A \gamma (1-p) - 2\alpha_B}{((1-p)+\gamma)^2} T_A - \frac{2\alpha_B}{(1-p)+\gamma} T_B$

(A15e) $R_A = \frac{\gamma}{(1-p)+\gamma} T_A$

(A15f) $R_B = \frac{1}{(1-p)+\gamma} T_A + T_B$

if $p = 0$, (A15) returns to (A6).

Under buyers' liability and a tariff, the problem is:

(A16) $\min_{R_A} C_A = \alpha_A R_A^2 + t\pi P$ s.t. $R_A + \left(1-p\right) P \geq T_A; \min_{R_B} C_B = \alpha_B {R_B}^2 - \pi P$ s.t. $R_B - P \geq T_B$

with $0 \leq p \leq 1$ and $t \geq 1$.

The first order conditions of are:

(A17a) $2\alpha_A R_A - \lambda_A = 0$

(A17b) $t\pi - \lambda_A (1-p) = 0$

(A17c) $R_A + (1-p)P - T_A = 0$

(A17d) $2\alpha_B R_B - \lambda_B = 0$

(A17e) $-\pi + \lambda_B = 0$

(A17f) $R_B - P - T_B = 0$

Total emissions fall by pP.

This solves as:

(A18a) $P = \frac{\alpha_A (1-p)}{\alpha_A (1-p)^2 + \alpha_B t} T_A - \frac{\alpha_B t}{\alpha_A (1-p)^2 + \alpha_B t} T_B$

(A18b) $\pi = \lambda_B = \frac{2\alpha_A \alpha_B (1-p)}{\alpha_A (1-p)^2 + \alpha_B t} T_A + \frac{2\alpha_A \alpha_B (1-p)^2}{\alpha_A (1-p)^2 + \alpha_B t} T_B$

(A18c) $\lambda_A = \frac{2\alpha_A \alpha_B t}{\alpha_A (1-p)^2 + \alpha_B t} T_A + \frac{2\alpha_A \alpha_B t (1-p)}{\alpha_A (1-p)^2 + \alpha_B t} T_B$

(A18d) $R_A = \frac{\alpha_B t}{\alpha_A (1-p)^2 + \alpha_B t} T_A + \frac{\alpha_B t(1-p)}{\alpha_A (1-p)^2 + \alpha_B t} T_B$

(A18e) $R_B = \frac{\alpha_A (1-p)}{\alpha_A (1-p)^2 + \alpha_B t} T_A + \frac{\alpha_A (1-p)^2}{\alpha_A (1-p)^2 + \alpha_B t} T_B$

If t=1, (A18) returns to (A3), with (1-p)=d. If p=0, (A18) returns to (A9). If t=1 and p=0, (A18) returns to (4).

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

(A19) $\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ s.t. $R_A + dP \geq T_A ; \min_{R_B} C_B = \alpha_B R_B{}^2 - \pi P$ s.t. $R_B - (1+\mu)P \geq T_B$

with $\mu \geq 0$ and $0 \leq d \leq 1$.

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 an import quota, the problem looks like:

(A22)

$\min_{R_A} C_A = \alpha_A R_A^2 + \pi P$ 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. $R_B - (1+\mu)P \geq T_B$

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

The first order conditions are:

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

(A23b) $\pi - \lambda_A + \lambda_C \gamma = 0$

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

(A23d) $R_A - \gamma P = 0$

(A23e) $2\alpha_B R_B - \lambda_B = 0$

(A23f) $-\pi + (1+\mu)\lambda_B = 0$

(A23g) $R_B - (1+\mu)P - T_B = 0$

Total emissions stay the same. This solves as:

(A24a) $P = \frac{1}{1+\gamma} T_A$

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

(A24c) $\lambda_B = \frac{2\alpha_B (1+\mu)}{1+\gamma} T_A + 2\alpha_B T_B = 2\alpha_B R_B$

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

(A24e) $\lambda_C = \frac{2\alpha_A \gamma - 2\alpha_B (1+\mu)^2}{(1+\gamma)^2} T_A - \frac{2\alpha_B (1+\mu)}{1+\gamma} T_B$

(A24f) $R_A = \frac{\gamma}{1+\gamma} T_A$

(A24g) $R_B = \frac{1+\mu}{1+\gamma} T_A + T_B$

If $\mu = 0$, (A24) returns to (A6).

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

(A25) $\min_{R_A} C_A = \alpha_A R_A^2 + t\pi P$ 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 $\mu \geq 0$ and $t \geq 1$.

The first order conditions are:

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

(A26b) $t\pi - \lambda_A = 0$

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

(A26d) $2\alpha_B R_B - \lambda_B = 0$

(A26e) $-\pi + \lambda_B(1+\mu) = 0$

(A26f) $R_B - (1+\mu)P - T_B = 0$

Total emissions fall by μP. This solves as:

(A27a) $P = \frac{\alpha_A}{\alpha_A + \alpha_B t(1+\mu)^2} T_A - \frac{\alpha_B t(1+\mu)}{\alpha_A + \alpha_B t(1+\mu)^2} T_B$

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

(A27c) $\lambda_A = \frac{2\alpha_A \alpha_B t(1+\mu)^2}{\alpha_A + \alpha_B t(1+\mu)^2} T_A + \frac{2\alpha_A \alpha_B t(1+\mu)}{\alpha_A + \alpha_B t(1+\mu)^2} T_B$

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

(A27e) $R_A = \frac{\alpha_B t(1+\mu)^2}{\alpha_A + \alpha_B t(1+\mu)^2} T_A + \frac{\alpha_B t(1+\mu)}{\alpha_A + \alpha_B t(1+\mu)^2} T_B$

(A27f) $R_B = \frac{\alpha_A (1+\mu)}{\alpha_A + \alpha_B t(1+\mu)^2} T_A + \frac{\alpha_A}{\alpha_A + \alpha_B t(1+\mu)^2} T_B$

If μ=0, (A27) returns to (A9). If t=1, (A27) returns to (A12). If μ=0 and t=1, (A27) returns to (4).

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Tables

Table I. 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 of the shadow prices
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	$\frac{2\alpha_A\alpha_B}{\alpha_A d^2+\alpha_B}T_A+\frac{2\alpha_A\alpha_B d}{\alpha_A d^2+\alpha_B}T_B$	$\frac{2\alpha_A\alpha_B d}{\alpha_A d^2+\alpha_B}T_A+\frac{2\alpha_A\alpha_B d^2}{\alpha_A d^2+\alpha_B}T_B$	$\frac{1}{d}$
Import Quota	$\frac{2\alpha_A\gamma^2+2\alpha_B}{(1+\gamma)^2}T_A+\frac{2\alpha_B}{1+\gamma}T_B$	$\frac{2\alpha_B}{1+\gamma}T_A+2\alpha_B T_B=2\alpha_B R_B$	$\frac{\left(\alpha_A\gamma^2+\alpha_B\right)T_A+\alpha_B\left(1+\gamma\right)T_B}{\alpha_B\left(1+\gamma\right)T_A+\alpha_B(1+\gamma)^2 T_B}$
Tariffs	$\frac{2\alpha_A\alpha_B t}{\alpha_A+\alpha_B t}T_A+\frac{2\alpha_A\alpha_B t}{\alpha_A+\alpha_B t}T_B$	$\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B t}T_A+\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B t}T_B$	$\frac{t}{1}$
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 Quota	$\frac{2\alpha_A\gamma^2+2\alpha_B}{((1-p)+\gamma)^2}T_A+\frac{2\alpha_B}{(1-p)+\gamma}T_B$	$\frac{2\alpha_B}{(1-p)+\gamma}T_A+2\alpha_B T_B=2\alpha_B R_B$	$\frac{\left(\alpha_A\gamma^2+\alpha_B\right)T_A+\alpha_B\left(1+\gamma-p\right)T_B}{\alpha_B\left(1+\gamma-p\right)T_A+\alpha_B(1+\gamma-p)^2 T_B}$
Buyers' Liability and Tariff	$\frac{2\alpha_A\alpha_B t}{\alpha_A(1-p)^2+\alpha_B t}T_A+\frac{2\alpha_A\alpha_B(1-p)t}{\alpha_A(1-p)^2+\alpha_B t}T_B$	$\frac{2\alpha_A\alpha_B(1-p)}{\alpha_A(1-p)^2+\alpha_B t}T_A+\frac{2\alpha_A\alpha_B(1-p)^2}{\alpha_A(1-p)^2+\alpha_B t}T_B$	$\frac{t}{1-p}$
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 Quota	$\frac{2\alpha_A\gamma^2+2\alpha_B(1+\mu)^2}{(1+\gamma)^2}T_A+\frac{2\alpha_B(1+\mu)}{1+\gamma}T_B$	$\frac{2\alpha_B(1+\mu)}{1+\gamma}T_A+2\alpha_B T_B=2\alpha_B R_B$	$\frac{\left(\alpha_A\gamma^2+\alpha_B(1+\mu)^2\right)T_A+\alpha_B(1+\gamma)(1+\mu)T_B}{\alpha_B(1+\gamma)\left((1+\mu)T_A+(1+\gamma)T_B\right)}$
Sellers' Liability and Tariff	$\frac{2\alpha_A\alpha_B t(1+\mu)^2}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B t(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$	$\frac{2\alpha_A\alpha_B(1+\mu)}{\alpha_A+\alpha_B t(1+\mu)^2}T_A+\frac{2\alpha_A\alpha_B}{\alpha_A+\alpha_B t(1+\mu)^2}T_B$	$\frac{t(1+\mu)}{1}$