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BUY COAL? DEPOSIT MARKETS PREVENT CARBON LEAKAGE

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ABSTRACT

If a coalition of countries implements climate policies, nonparticipants tend to consume more, pollute more, and invest too little in renewable energy sources. In response, the coalition's equilibrium policy distorts trade and is not time-consistent. This paper derives conditions for when trading fossil fuel deposits increase efficiency. In isolation, a bilateral transaction may occur too often or too seldom compared to the optimum. However, when the market clears, the above-mentioned problems vanish, the first-best is implemented, and the coalition finds it optimal to rely entirely on supply-side policies, which are simple to implement in practice.

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1. Introduction

Some countries are unlikely to ever join a legally binding climate treaty. Only 37 countries are currently committed to binding targets under the Kyoto Protocol. Since these commitments are set to expire in 2012, the United Nations negotiated the Copenhagen Accord in December, 2009. The Accord recognizes the need to reduce global CO_2 emissions but it does not legally bind the signatories in any way. Despite this, it was unable to secure full participation.

While nonparticipants are likely to pollute too much, the main concern is that they might undo the climate coalition's effort. When the coalition introduces regulation, world prices change, market shares shift, industries relocate, and nonparticipants may end up emitting more than they did before. The International Panel on Climate Change (IPCC, 2007:665) defines carbon leakage as "the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries." Most estimates of leakage are in the interval 5-25 percent, but the number can be higher if the coalition is small, the policy ambitious, and the time horizon long.[1] Carbon leakage discourages countries from reducing pollution and may motivate them to set border taxes or tariffs on trade.[2] Thus, Frankel (2009:507) concludes, "it is essential to find ways to address concerns about competitiveness and leakage."

This paper considers a coalition of countries harmed by the consumption of fossil fuel. Countries outside of the coalition are naturally polluting too much compared to the optimum. In addition, if the coalition reduces its demand for fossil fuel, the world price for fuel declines and the nonparticipating countries consume more. If the coalition shrinks its supply of fossil fuel, the nonparticipants increase their supply. If countries can invest

[1] See the surveys in IPCC (2007), Frankel (2009), and Rauscher (1997). The variation in estimates hinges on a number of factors. Elliott et al. (2010) estimate leakage rates of 15-25 percent, increasing in the level of the carbon tax. Babiker (2005) takes a long–term perspective by allowing firms to enter and exit, and finds that leakage can be up to 130 percent. For the countries signing the Kyoto Protocol, Böhringer and Löschel (2002: 152) estimate leakage to have increased from 22 to 28 percent when the US dropped out.

[2] While estimates of leakage vary, the *Financial Times* writes "the fear of it is enough to persuade many companies to lobby their governments against carbon regulation, or in favour of punitive measures such as border taxes on imports" (Dec. 11, 2009), but: "the danger is that arguments over border taxes could make an agreement even more difficult to negotiate" (Nov. 5, 2009) and it is an "easy way to start a trade war" (Dec. 9, 2009).

in renewable energy sources, nonparticipants invest too little compared to the first-best levels. For the coalition, regulating their own consumption, production, and trade is a second-best solution. However, in equilibrium, the coalition sets policies so as to influence its terms of trade as well as the environment.

The first main result (Theorem 1) provides a condition for when there exist gains from bilaterally trading a marginal fossil fuel deposit. The coalition may benefit from purchasing the right to exploit a fossil fuel deposit that is, in any case, quite polluting or costly to exploit. After such a purchase, the coalition will preserve rather than exploit the deposit. Since this alters the world fuel price, third parties may thus suffer or benefit, depending on whether they are net importers or exporters of fuel. Hence, bilateral trade may occur too often or too seldom.

Nevertheless, Theorem 2 shows that, once the market for deposits clear, all the above-mentioned problems vanish and the first-best outcome is implemented. In equilibrium, the coalition purchases the right to exploit the fossil fuel deposits that are most polluting or very costly to exploit. As a result, the nonparticipants' supply becomes locally inelastic, the supply-side leakage is eliminated, and the coalition chooses to rely entirely on reducing its supply and not its demand. Consequently, the consumption price is equalized across countries, and all investments are then efficient.

Although the model is simple and stylized, the results strengthen the case for a climate policy that focuses on the supply side, including the supply of foreign countries. In reality, a market for exploiting fossil fuel deposits already exists, since countries frequently sell, auction, license, or outsource the right to extract their own oil and other minerals to international companies as well as to major countries such as India and China.[3] Instead of inventing such a market, the paper is analyzing its potential as a climate policy. Note that the first-best policy is simple to implement once the market for deposits has cleared: the coalition only needs to set aside certain deposits by, for example, specifying an extraction fee high enough to make them unprofitable. The coalition then has neither the desire nor the need to regulate consumption or trade in addition. In practice, it is simpler to tax production than consumption because of the relatively few sources (Elliott et al., 2010).

[3]For a history of the oil industry and the involvements of governments, see Yergin (2009).

Furthermore, rather than purchasing foreign deposits, a leasing arrangement may suffice.

The paper combines two strands of literature. On the one hand, there is a growing literature on carbon leakage, based on the prediction that not all countries will participate in a climate coalition.[4] Markusen (1975) showed that one country's environmental policy affects world prices and thus both consumption and pollution abroad. In addition, capital may relocate (Rauscher, 1997) and firms might move (Markusen et al., 1993, 1995). The typical second-best remedy is to set tariffs or border taxes (Elliott et al., 2010; Rauscher, 1997; Hoel, 1996; and Markusen, 1975).[5] However, countries have incentives to let the tariff influence their terms of trade.[6] In fact, Liski and Tahvonen (2004) show that a country may *benefit* from being harmed by pollution if this justifies border measures. Most of this literature focuses on demand-side climate policies. In many ways, Hoel (1994) provides the most general model by also allowing the coalition to limit its supply. Since the game by Hoel is a proper subgame of the game I present, this paper generalizes several of the above results before obtaining its main results.

On the other hand, the literature following Coase (1960) argues that the parties can attain efficiency by negotiating activities ex post, *no matter* the allocation of property rights. The coalition should then be able to negotiate with and bribe nonparticipating countries to reduce their consumption of fuel. The literature on leakage must thus assume that transaction (or contracting) costs prevent such effective ex post negotiations. Coase (1960: 15) admits that such transaction costs often exist. But, rather than predicting leakages, Coase (1937 and 1960) suggested that such transactions should and will take place inside "the firm." This has inspired Williamson's (1975) theory of the firm as well as literatures on vertical integration and horizontal mergers.[7]

[4] Although there is no consensus on how to model coalition formation, environmental agreements have often been modeled as a two-stage process: first, a country decides whether to participate; second, the participants maximize their joint utility by choosing appropriate policies. This procedure typically leads to free-riding (see Barrett, 2005, for a survey of this literature).

[5] Certain environmentally motivated border measures are indeed permitted by the WTO, and the Montreal Protocol on Substances that Deplete the Ozone Layer, signed in 1987, does contain the possibility of restricting trade from noncompliant countries.

[6] Rauscher (1997:3) observes that "Green arguments can easily be abused to justify trade restrictions that are in reality only protectionist measures and it is often difficult to discriminate between true and pretended environmentalism."

[7] See Gaudet and Salant (1991) or Kamien and Zang (1990) on horizontal mergers, and the survey by Katz (1989) or Rey and Tirole (2007) on vertical integration.

The two strands of literature have remained distinct since it would not be realistic to politically integrate "only" to mitigate climate change. However, note that Perry and Porter (1985) model mergers basically as trade in input factors. Trading input factors may be possible even if Coaseian bargining over output is not: First, the ownership of production factors is tangible and possible to protect, while contracts on output is not. Second, in international policies, it might be politically difficult to persuade voters to pay for an emission reduction abroad, but the policy is rather conventional if the country, in return, receives the right to exploit certain deposits. Third, such transfers go to deposit-owners rather than consumers (or their governments). This may be cheaper, as argued in Section 4.6. Finally, it may be possible to estimate extraction costs, dictating the deposit price, but it can be quite hard to verify the utility-reduction dictating the compensation for abatement.

It is apriori not clear whether a market for inputs is sufficient for efficiency.[8] In fact, several scholars have shown that the Coase Theorem fails when there are more than two players and/or there are externalities on third parties.[9] This motivates a literature studying when factor trade leads to concentration of market power.[10] To my knowledge, Bohm (1993) is the only other paper studying whether analogous trade in fossil fuel deposits may help a coalition curb climate change. Assuming linear demand and supply curves, Bohm investigated when a reduction in consumption should be accompanied by an identical reduction in supply. This may necessitate purchasing or leasing foreign deposits, and Bohm documented that this could be realistic in practice.[11]

[8] A literature on international trade, initiated by Mundell (1957) and surveyed by Jones (2000), investigates whether trade in input factors is a perfect substitute to trade in final goods. In this paper, trading factors is strictly better since there are externalities and the factor owner can unilaterally decide whether the factor is to be used for production.

[9] For example, efficiency may fail if participation is voluntary (Dixit and Olson, 2000) or side contracting possible (Jackson and Wilkie, 2005), particularly if there are externalities on third parties (Segal, 1999).

[10] For example, Esö et al. (2010) investigate when a market for capacity leads an industry to maximize its total surplus. In the electricity sector, trading the transmission rights before generating power may help the providers maximize joint profit (Joskow and Tirole, 2000). These papers suggest that trading inputs may substitute for ex post negotiation, but they study concentration of market powers and not the internalization of externalities, more generally.

[11] In contrast, the literature on tradable pollution permits (surveyed by Tietenberg, 2006), presumes that all trading countries are participating in the coalition. Trading permits *within* the coalition is just a way of obtaining a certain emission reduction efficiently and it does not eliminate leakages.

Building on these contributions, Theorem 1 below states conditions under which a bilateral trade in inputs is mutually beneficial - even if it reduces global welfare. When the deposit market clears, Theorem 2 shows that the first-best is implemented in the benchmark model. Thus, efficiency is often obtained, even if Coaseian bargaining on output is impossible ex post, if just key inputs are tradable ex ante.

This insight can certainly be applied to other situations. For example, boycotting timber is an ineffective way of preserving tropical forests since the timber price thereby decline, leading other buyers to increase their consumption. A more effective solution, according to this paper, is to pay developing countries to reduce their deforestation. The recent emergence of REDD (Reducing Emissions from Deforestation and Forest Degradation) funds is consistent with this conclusion. Such funds have now been set up by the United Nations, the World Bank, and Norway.

While the next section presents the basic model, the main results are discussed in Section 3. Section 4 generalizes the model and the results by allowing for investments in technologies, multiple periods, and heterogeneous fossil fuels. That section also discusses alternative market structures and endogenizes participation. Section 5 concludes and addresses the limitations of the results. The Appendix contains all the proofs.

2. The basic model

There are two sets of countries: one set, M, participates in the climate treaty while the other set, N, does not. This paper focuses on the interaction between these sets and thus abstracts from internal conflicts or decision-making within M. I will thus treat M as one player or country. The nonparticipating countries in N interact with each other and with M only through markets.

Every country benefits from consuming energy, but fuel is costly to extract. If a country $i \in M \cup N$ consumes y_i units of fuel, i's benefit is given by the function $B_i(y_i)$, which is twice differentiable and satisfies $B_i' > 0 \geq B_i''$. Country i's cost of supplying or extracting x_i units is represented by an increasing and strictly convex function, $C_i(x_i)$. There is a world market for fuel and p measures the equilibrium price. Assuming quasilinear utility functions, the objective functions are

$$
\begin{aligned}
U_i &= B_i(y_i) - C_i(x_i) - p(y_i - x_i) \text{ if } i \in N, \\
U_i &= B_i(y_i) - C_i(x_i) - p(y_i - x_i) - H\left(\sum_{M \cup N} x_i\right) \text{ if } i = M,
\end{aligned}
$$

where the harm $H(.)$, experienced by M, is a strictly increasing and convex function. I assume that only M, and not $i \in N$, takes the environmental harm into account in its objective function. In fact, country i's indifference may explain why it is not participating in the climate treaty in the first place. Alternatively, one could assume that nonparticipants act *as if* they have no environmental concerns, because, for example, domestic forces hinder the implementation of a climate policy unless the government has committed itself by signing an international treaty.[12] The extension in Section 4.4 allows $i \in N$ to be harmed by pollution. Section 4.3 permits various fuels (such as gas and coal) to differ in their environmental impact.

I assume that country $i \in N$ chooses x_i and y_i taking the fuel price as given. This is natural if the decisions to consume and produce are decentralized to agents with little market power. Thus, this assumption does not imply that i, as a country, is tiny. Alternatively, the price-taking assumption would hold if p followed from the climate policy set by M earlier in the game. In any case, this assumption is relaxed in Section 4.5.

To cope with the environmental harm, M sets environmental policies. This amounts to setting x_M and y_M if relying on quotas for extraction and consumption. The price for fuel will then adjust to ensure that the market clears:

$$
\sum_{M \cup N} y_i = \sum_{M \cup N} x_i.
$$

Since the market-clearing condition must hold, and $\sum_N (y_i - x_i) = x_M - y_M$ depends on p, the outcome would be identical if M could instead choose x_M and p and let y_M clear the market. Similarly, M may regulate x_M and y_M by setting a tax τ_x on domestic production, a tax τ_y on consumption, and perhaps even a tariff τ_I on imports (or such an export subsidy). Any tax vector $\tau = \{\tau_x, \tau_y, \tau_I\}$ is going to pin down x_M, y_M, and

[12] Similarly, it may be difficult to liberalize trade policies for political reasons, but being committed by a trade treaty can help (Hoekman and Kostecki, 2001).

p. The outcome is going to be identical no matter how M influences these variables, and the choice between quotas and taxes is therefore immaterial in this model.[13] In any case, the equilibrium fuel price is influenced by M's policies and M does, of course, take this effect into account.

The novel part of the model is that I endogenize $C_i(.)$ by allowing for trade in deposits.[14] There is a continuum of deposits, and the cost function $C_i(.)$ implicitly orders a country's deposits according to their extraction costs. This is natural, since a country that is extracting x_i units would always prefer to first extract the deposits that have the lowest extraction costs. A small deposit allocated between x_i' and x_i'' is characterized by its size $\Delta \equiv x_i'' - x_i'$ and by its marginal extraction cost $c \equiv [C_i(x_i'') - C_i(x_i')]/\Delta$. In the deposit market, M may purchase from $i \in N$ the right to exploit such a deposit. This would change both cost functions from the solid to the dotted lines in Figure 1. As a result, C_i' may be a correspondence, and not a function, if we define $C_i'(x_i) \equiv [\lim_{\epsilon\uparrow 0} C_i'(x_i+\epsilon), \lim_{\epsilon\downarrow 0} C_i'(x_i+\epsilon)]$.

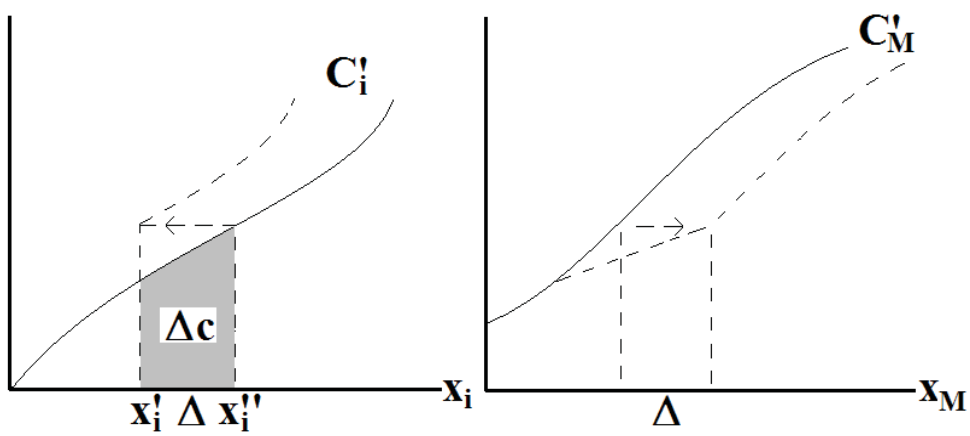

Figure 1: If country i sells deposits to M, both cost curves shift

The market is cleared if and only if there exists no pair of countries $(i, j) \in (M \cup N)^2$ and no price such that both i and j strictly benefit from transferring the right to exploit

[13]This is in line with Weitzman (1974), who shows that uncertainty regarding the parameters is necessary to rank quotas and taxes.

[14]Of course, the aggregate world-wide cost function is exogenously given. For any allocation of deposits, we could write it as:

$$C(x) = \min_{\{x_i\}} \sum_{M\cup N} C_i(x_i) \text{ s.t. } \sum_{M\cup N} x_i = x.$$

a deposit from i to j at that price. If this condition is not satisfied, there are still gains from trade. With this equilibrium concept, I can check whether a particular allocation of deposits, leading to a particular $C_i(.)$ and $C_M(.)$, constitutes an equilibrium.

Note that I do not need to specify a market structure leading to this equilibrium. But, as discussed in Section 4.6, there are several possibilities. For example, one could let $i \in (M \cup N)$ make a take-it-or-leave-it offer to the other countries, conditional on the offer being accepted by everyone.

The timing of the game is given by Figure 2: after the deposit market clears, M sets its policies and, finally, the fossil fuel market clears.[15] The next section solves the game by backwards induction in order to characterize all subgame-perfect equilibria. Several extensions are discussed in Section 4.

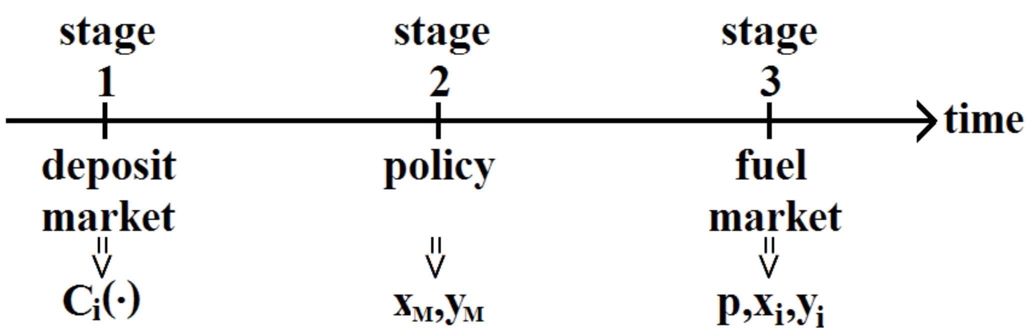

Figure 2: Timing of the game

3. The equilibrium

As a benchmark, note that the first-best is given by equalizing every country's marginal benefit of consumption to the marginal cost of production plus the marginal environmental harm. For any given allocation of deposits, this means:

$$\max_{\{x_i\},\{y_i\}} \sum_{M\cup N} U_i \Rightarrow B'_j\left(y_j^*\right) - H'\left(\sum_{M\cup N} x_i^*\right) \in C'_i\left(x_i^*\right)\ \forall i,j \in M\cup N. \tag{3.1}$$

[15] I do not allow nonparticipating governments to set policies influencing supply and demand. Allowing for this would complicate the analysis without altering the main result, as argued in Section 4.5.

3.1. The market for fuel

At the third stage, each nonparticipating country, $i \in N$, simply sets its marginal benefit such that:

$$B_i'(y_i) = p \Rightarrow y_i = D_i(p) \equiv B_i'^{-1}(p). \tag{3.2}$$

The demand by $i \in N$ is thus given by $D_i(p)$. On the production side, $C_i'(x_i) = p$, if $C_i'(x_i)$ is singular. If $C_i'(x_i)$ is nonsingular, then $p \in C_i'(x_i)$. Since $C_i(.)$ is a strictly convex function, the correspondence $C_i'(.)$ is invertible and its inverse, $x_i = S_i(p) \equiv C_i'^{-1}(p)$, is a function:

$$p \in C_i'(x_i) \quad \Rightarrow x_i = S_i(p) \equiv C_i'^{-1}(p) \, \forall i \in N. \tag{3.3}$$

Obviously, if $C_i'(x_i)$ is nonsingular at x_i, then $S_i'(p) = 0$ at each $p \in C_i'(x_i)$.

For the coalition M, supply and demand depend on the policies determined at the second stage.[16] In equilibrium, p is such that the market clears:

$$\begin{aligned} I \equiv y_M - x_M &= S(p) - D(p), \text{ where} \\ S(p) &\equiv \sum_N S_i(p), \\ D(p) &\equiv \sum_N D_i(p). \end{aligned} \tag{3.4}$$

3.2. Equilibrium policies

At the second stage, M chooses x_M and y_M to maximize

$$U_M = B_M(y_M) - C_M(x_M) - H\left(x_M + \sum_N x_i\right) - p(y_M - x_M),$$

subject to (3.2)-(3.4):

[16] For example, y_M could be set directly by a consumption quota, while x_M could be set directly by an extraction quota. Alternatively, the government may specify a tax vector τ and redistribute the revenues lump sum within M. If the consumers and suppliers in M are price-takers when trading fuel, x_M and y_M would be given by:

$$\left\{ \begin{array}{c} B_M'(y_M) = p + \tau_y + \tau_I \\ C_M'(x_M) = p - \tau_x + \tau_I \end{array} \right\} \Rightarrow \left\{ \begin{array}{c} y_M = D_M(p + \tau_y + \tau_I) \equiv B_M'^{-1}(p + \tau_y + \tau_I) \\ x_M = S_M(p - \tau_x + \tau_I) \equiv C_M'^{-1}(p - \tau_x + \tau_I) \end{array} \right\}.$$

Clearly, x_M and y_M can be implemented by any two of $\{\tau_x, \tau_y, \tau_I\}$.

Lemma 1. *M's equilibrium policy implements:*

$$B_M'(y_M) = p + \left(\frac{S'(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)}, \tag{3.5}$$

$$C_M'(x_M) \ni p - \left(1 - \frac{S'(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)}. \tag{3.6}$$

Compared to the first-best (3.1), the equilibrium is generally quite different. Neither marginal benefits nor marginal costs are equalized across countries. M understands that if it reduces its supply, p increases, and N extracts more. If, instead, M reduces its consumption, p declines, and N consumes more. Conditions (3.5)-(3.6) show how M balances these two types of leakages. If the last term were negligible (i.e., if $y_M = x_M$), M would focus on demand-side policies and reduce y_M, if foreign supply were elastic relative to demand. But if demand were more elastic than supply, M would focus on reducing its supply x_M rather than its demand.

In addition, the last term in (3.5)-(3.6) show that M sets policies considering their impact on its terms of trade. If M is exporting fossil fuel, M prefers to reduce its production and increase its consumption, since both changes increase the price M receives for its exports. M's ability to affect the equilibrium price is another reason - in addition to free-riding and the two types of leakages - why the first-best is generally not achieved.

Lemma 1 is, basically, identical to Hoel's (1994) equations (9)-(10). Hoel shows that M's ideal policy can be implemented by taxes on domestic consumption and production:

$$\tau_y = B_M'(y_M) - p = \left(\frac{S'(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)},$$

$$\tau_x = p - C_M'(x_M) = \left(1 - \frac{S'(p)}{S'(p) - D'(p)}\right) H' - \frac{y_M - x_M}{S'(p) - D'(p)}.$$

Note that the sum of the taxes is always equal to H', the marginal harm.

Alternatively, (3.5)-(3.6) can be implemented by a production tax and a tariff (while $\tau_y = 0$). The equilibrium policies are then as in Markusen (1975) and Hoel (1996):

$$\tau_I = B_M'(y_M) - p = \left(\frac{S'(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)},$$

$$\tau_x = B_M'(y_M) - C_M'(x_M) = H'.$$

The production tax should be Pigouvian and the emission from M's supply is thus independent of the terms-of-trade effects. This is in line with Proposition 8 in Copeland and

Taylor (1995). The leakages are dealt with by the tariff. Since the tariff reduces domestic consumption, it should be high if the demand-side leakage is low while the supply-side leakage is large. To affect its terms of trade, M sets a high tariff if it is importing but a low tariff (or export subsidy) if it is exporting.

3.3. When are there gains from trade?

Consider the first stage of the game. Suppose country $i \in N$ considers selling a deposit to M. When are there gains from such a trade?

Theorem 1. *Consider a marginal deposit of size Δ and with marginal extraction cost $c < p$, owned by $i \in N$. If i transfers the deposit to M, then*
(a) $U_M + U_i$ increases if and only if (3.7) holds, but
(b) $\sum_{M \cup N} U_i$ increases if and only if (3.8) holds:

$$\max\{0, c + H' - B_M'(y_M)\} + (x_i - y_i)\frac{\partial p}{\partial \Delta} > 0, \quad (3.7)$$

$$\max\{0, c + H' - B_M'(y_M)\} + \sum_N (x_i - y_i)\frac{\partial p}{\partial \Delta} > 0, \text{ where} \quad (3.8)$$

$$\frac{\partial p}{\partial \Delta} > 0.$$

Part (a) describes when i and M can benefit if i sells the deposit to M. If (3.7) holds, there exists a price such that i and M are both strictly better off by trading at this price. Part (b) states when such a trade is beneficial for the world as a whole.

To understand the theorem, consider first part (a), and suppose that the last term in (3.7) is negligible (for example, because $x_i \approx y_i$). In this case, trade is beneficial for i and M if $c \in (B_M'(y_M) - H, p)$. While such a deposit would be exploited when owned by $i \in N$, after the transaction M prefers to preserve it, since the revenues gained by exploiting it are less than the environmental harm.

Things are somewhat more complicated when $x_i \neq y_i$. After selling the deposit to M, country i exports less and M imports less. By Lemma 1, M finds it optimal to rely less on supply-side and more on demand-side policies, and the equilibrium price is slightly reduced. Thus, $\partial p / \partial \Delta > 0$. M is indifferent to this change in the price, since M is always setting the policies such that the price is optimal from M's point of view. However, the increase in p is beneficial to i if i is a net exporter of fuel. Thus, an exporter is *always* willing to sell deposits satisfying $c \in (p, B'_M(y_M) - H)$. In contrast, if $i \in N$ is a net importer, then the increase in p is harmful to i; country i may thus be unwilling to sell the deposit even if it has a high extraction cost and M would have preserved it rather than exploited it. In sum, it is more likely that i sells the deposit to M if i is an exporter and if c is so high that M will preserve it. The larger $(x_i - y_i)$ and c are, the larger are the gains from trade.

Part (b) states when such a trade is beneficial for the society as a whole. Condition (3.8) is different from (3.7), thanks to the effect on p. If $i \in N$ sells a deposit to M, p increases and, for country $j \in N \backslash i$, this is beneficial if j is an exporter, but harmful if j is an importer. Thus, if the other countries are, as a group, importing, then i and M may trade a deposit even though this reduces welfare for the world as a whole. If the other countries are, as a group, exporting, then i may not sell a deposit to M even though such a trade would be beneficial for the world.

The above reasoning presumes that i takes into account that its sale or purchase of deposits may affect the equilibrium price of fuel. This can be consistent with the assumption that i takes the fuel price as given at stage 3: The individual *consumers* and *producers* in country i may take the fuel price as given, even if their government realizes that selling national deposits may (if only marginally) affect the world fuel price. Alternatively, if the fuel price is determined by M's policy at stage 2, it is fixed for everyone at stage 3 - even if i's sale at stage 1 can influence M's policy at stage 2 and thus the price at stage 3.[17]

3.4. The deposit market equilibrium

The market clears when there exists no pair of countries that would both strictly benefit from trading some of their deposits at some price. The market equilibrium cannot be unique since, if two countries exploit one deposit each, they could easily exchange those two deposits, which would constitute another equilibrium. Nevertheless, I can state the

[17] Instead of maximizing U_M by choosing x_M and y_M at stage 2, suppose M chooses p and, say, x_M. Also in this case, (3.2)-(3.4) must hold and the first-order conditions for the policy are going to be the same.

following result:

Theorem 2. *In every equilibrium of the deposit market, M's equilibrium policy (3.5)-(3.6) implements the first-best (3.1).*

This result might be surprising since (3.5) appears to be substantially different from the first-best (3.1). The equilibrium from stage 2 is generally inefficient because of free-riding, consumption leakage, production leakage, and M's market power. In addition, Theorem 1 states that i and M may trade too much or too little. It turns out that all these problems vanish once the deposit market has cleared.

Theorem 2 follows from Lemmas 2 and 3:

Lemma 2. *In every equilibrium,* $x_i = y_i \; \forall i \in M \cup N$.

When the market for deposits clears, every country expects to rely on neither imports nor exports of fossil fuel. That this is a feasible equilibrium should not be surprising since M can equally well sell a deposit to i instead of selling the fuel exploited afterwards. Lemma 2 goes further, however, in claiming that $x_i = y_i$ always. This follows from Theorem 1: Suppose $i \in N$ is an importer of fuel. If M sells a small deposit to i, which is such that any owner would exploit it ($c < H' - B'_M$), then M is exports less afterwards. According to Lemma 1, p declines, which is beneficial for the importing country i. Thus, i is willing to pay more for the deposit than M requires for giving it up. In equilibrium, therefore, i cannot be importing. For similar reasons, i cannot be exporting, either.

The next stepping stone for Theorem 2 is:

Lemma 3. *In every equilibrium,* $S_i'(p) = 0 \; \forall i \in N$.

In other words, $C_i'(.)$ is vertical and jumps at the equilibrium x_i, $i \in N$. As suggested by Theorem 1, the reason is that M is willing to purchase the deposits which $i \in N$ is almost indifferent about exploiting. If the marginal cost c of exploiting a deposit is almost as high as the price p, then i is willing to sell the deposit for a low price $(p - c)$. If M purchases this deposit without exploiting it, M's benefit is reduced pollution. This gain is roughly $H' > 0$, certainly larger than the price for the deposit when $c \approx p$. Intuitively, if

M considers purchasing and preserving any of i's deposits, it is cheapest to buy deposits that are expensive to exploit. Hence, when the market for deposits clears, the supply of $i \in N$ is locally inelastic.

Combined, Lemmas 1-3 imply that $B_M'(y_M) = p = B_i'(y_i) \, \forall i \in N$. Since the supply of country $i \in N$ is locally inelastic, M does not fear supply-side leakage, and it can rely entirely on supply-side politics. Moreover, since there is no need to regulate demand, there is no consumption leakage and the marginal benefits of fossil fuel are equalized across countries. Deposits that are profitable but socially inefficient to exploit, $c \in (p - H', p)$, are purchased (according to Theorem 1) and preserved (in line with Lemma 1) by M.

The policy is simple to implement in practice. Instead of calculating taxes for consumption and production, M simply purchases the deposits that are most expensive to exploit. Thereafter, M implements the first-best by setting aside these deposits, or by imposing an extraction tax ($\tau_x = H'$) high enough to make them unprofitable. Finally, market forces equalize marginal benefits and neither demand nor trade needs regulation (i.e., $\tau_y = \tau_I = 0$).

3.5. Examples

Symmetric example: The outcome is particularly clean if the supply and demand curves are initially identical and linear in every country:

$$\begin{aligned} B_i(y_i) &= by_i - ay_i^2/2, \\ C_i(x_i) &= cx_i^2/2 \; \forall i \in N. \end{aligned}$$

Let m measure the number of members in M, and let each face the marginal harm h, such that

$$H(.) = mh(x_M + x_1).$$

Without a deposit market, $i \in N$ would consume and supply x' in Figure 3, while $i \in M$ would consume and extract x^*. The area of the triangle $\alpha + \beta$ measures the social loss as well as the private cost for $i \in N$ of reducing its supply from x' to x^*. With a deposit market, M purchases all deposits with marginal extraction costs between $p^* - hm$ and p^*. The supply curve of N shifts from C_i' to C_N', while the supply curve of

M shifts from C_i' to C_M'. With the extraction tax hm in M, every country extracts x^* and the equilibrium consumption price is p^*. The price for these deposits is $\alpha + \beta$ if M makes a take-it-or-leave-it offer, but twice this amount if some nonparticipant makes a take-it-or-leave-it offer.

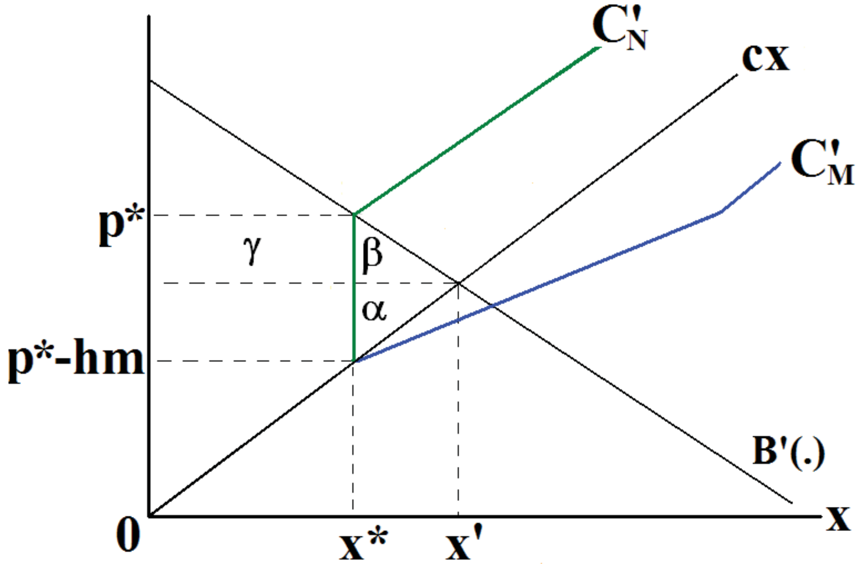

Figure 3: M purchases deposits with marginal costs between $p^* - hm$ and p^* and implements the first-best.

Asymmetric example: Take the symmetric example, but suppose that nonparticipating countries can be divide into consuming versus producing countries. The outcome is first-best, as before, but the deposit price may differ. If M can make the take-it-or-leave-it offer, it needs to pay only α if every marginal deposit has a separate owner. If there is a single owner, M needs to pay $\alpha - \gamma$. This sum may well be negative, since the seller is then glad to give up some of its deposits when it anticipates that, as a consequence, the price-setter M is going to increase the price on fuel. Purchasing inputs might thus be substantially cheaper than Coaseian bargaining to reduce nonparticipants' consumption.

4. Generalizing the result

4.1. Endogenous technology

Developing new technology is a central issue in the debate on how to cope with climate change. An important extension of the above model is thus to endogenize the technologies, and let countries invest in them. This extension, it turns out, strengthens the case for a market in deposits.

Suppose that every $i \in M \cup N$ can invest r_i in technology at cost $k_i(r_i)$, where $k_i'(.), k_i''(.) > 0$. To simplify, there are no spillovers or trade in technologies. The new technology is a substitute for polluting and it can represent, for example, renewable energy sources.[18] Thus, country i consumes energy from two sources and we may write its total benefit as $\widetilde{B}_i(y_i + r_i)$. Pre-investment policy refers to the case where investments take place between stage 2 and stage 3. Post-investment policy refers to the situation where they take place between stage 1 and stage 2. Solving the game by backwards induction, I first solve the game for a generic distribution of deposits.

To begin, assume that $i \in M \cup N$ is a price-taker when investing. This could be the case, for example, because investments are made by private entities in country i. Then, $\widetilde{B}_i'(.)$ is the willingness to pay for new technology in country i. Whether M's policy has been set, or will be set, in equilibrium:

$$\widetilde{B}_i'(y_i + r_i) = k_i'(r_i) \ \forall i \in M \cup N.$$

Is M's investment level r_M optimal? From M's point of view, it is. While a larger r_M decreases the need for fuel and thus the equilibrium fuel price, p is optimally chosen (or influenced) by M at the policy stage. By the envelope theorem, M's marginal value of r_M is simply $\widetilde{B}_M'(.)$. But the lower p, following a larger r_M, is beneficial to the nonparticipants if they are, as a group, importing. If $x_M < y_M$, the nonparticipants are, as a group, exporting. The larger r_M would then harm them.

Proposition 1. *The investment level r_M is smaller (larger) than the socially optimal level if and only if $x_M > y_M$ ($x_M < y_M$).*

[18] Allowing for investments in extraction technologies would be interesting but has been omitted to save space.

Are the investments of $i \in N$ optimal? A larger r_i reduces the need to buy fossil fuel, and the price declines. This is good for an importer but, from a social point of view, the sum of these terms-of-trade effects cancel.[19] However, the lower price reduces supply when supply is somewhat elastic (i.e., when $S' > 0$) and emissions then decline as well. Since this benefit is not internalized by $i \in N$, it invests too little compared to the social optimum when $S' > 0$, no matter how the investments are times.

Proposition 2. *(i) For every $i \in N$, the investment level r_i is lower than the socially optimal level, and it is* strictly *lower if and only if $S'(p) > 0$. (ii) The benefit for M of i's marginal investment is given by:*

$$\frac{\partial U_M}{\partial r_i} = \left(\frac{S'(p)}{\sum_N \left(S_i'(p) - 1/B_i''(p) \right)} \right) H' + \frac{y_M - x_M}{\sum_N \left(S_i'(p) - 1/B_i''(p) \right)} \; \forall i \in N. \tag{4.1}$$

The first term on the right-hand side of (4.1) is positive and captures the environmental gain when new technology reduces emissions. The second term is positive unless M is a net exporter of fuel. If M were exporting so much that the right-hand side of (4.1) were negative, M would be harmed by a larger r_i, $i \in N$, since that would reduce p and thus M's revenues. But otherwise, M would like a nonparticipant to invest more.

If M's policies are set after the investments are fixed, then $D_i'(.) = 1/B_i''(p)$ and, combining (4.1) and (3.5),

$$\partial U_M / \partial r_i = \widetilde{B}_i \left(y_i + r_i \right) - p,$$

which is equal to M's ideal consumption tax, or tariff. When this tax is positive, M strictly benefits from a marginally larger r_i, $i \in N$. If it could, M would then like to share its technology with i, or to invest directly in the nonparticipating countries.

If policies are set before investments, M can indeed influence i's investment. To encourage investments, M sets policies that generate a high fuel price. This can be done by restricting M's supply rather than its demand. Thus, pre-investment policies may rely more on supply-side politics and less on demand-side politics than would post-investment policies.

[19] In contrast to M, $i \in N$ does not set p and it does indeed care about how r_i affects p. Thus, if $i, j \in N$, $i \neq j$, we can write $\partial U_i / \partial r_i = \widetilde{B}_i'(.) - (y_i - x_i) \partial p / \partial r_i$, $\partial U_j / \partial r_i = -(y_j - x_j) \partial p / \partial r_i$ and $\partial U_M / \partial r_i = -(y_i - x_i) \partial p / \partial r_i - H'(.) \partial \left(\sum_N x_i \right) / \partial r_i$. Summing over these, the terms-of-trade effects cancel since $\sum_{M \cup N} (y_i - x_i) = 0$.

Proposition 3. *The equilibrium policy is given by Lemma 1 whether the policy is chosen before or after the investments. But the demand is more elastic when the policy is chosen first:*

$$D_i'(.) = 1/\widetilde{B}_i''(y_i + r_i) - 1/k_i''(r_i) < 0 \text{ for pre-investment policies;}$$
$$D_i'(.) = 1/\widetilde{B}_i''(y_i + r_i) < 0 \text{ for post-investment policies.}$$

If M sets policies before the investment stage, demand is more elastic. A larger p is then both reducing $y_i + r_i$ and increasing r_i, thus leading to a further decline in y_i. If the last two terms in (3.5) are positive, they decrease in $|D_i'(.)|$, ceteris paribus. As a consequence, x_M must decline while y_M must increase. Since the right-hand side can be interpreted as a consumption tax or a tariff, this tax should thus decrease while the extraction tax should increase.

Proposition 3 implies that M's optimal policy is sensitive to the particular timing. While M would prefer to announce tough supply-side policies before the investment stage in order to encourage investments, after the investment stage it prefers to rely more on demand-side politics. If a production tax and a tariff are used, M prefers to announce a low tariff before countries invest, but raise it afterwards. The ideal policy of M is thus not time-consistent.

In summary, for a generic distribution of deposits, investments in renewable energy are suboptimal for all countries. Nonparticipants invest too little, amplifying their existing overpollution. To encourage them to invest more, M would like to commit to tough supply-side policies rather than demand-side policies, but this policy may not be time-consistent.

For these reasons, the gains from trade are actually larger than in Section 3. If M purchases a deposit from $i \in N$, then p increases, i invests more, and M benefits more. When the deposit market clears, the outcome is efficient. Also for this case, Theorem 2 continues to hold:

Theorem 2 (ii). *In every equilibrium of the deposit market, M's equilibrium policy implements the first-best, whether it is chosen before or after investments.*

The result follows, almost as a corollary, from Propositions 1-3 and Lemmas 1-3. *If* the equilibrium in the deposit market is as described in Section 3.3, then $y_i = x_i$ and M's investment is optimal, according to Proposition 1. Lemma 3 states that $S_i'(.) = 0 \forall i \in N$, and Proposition 2 then implies that all countries invest optimally. Since the equilibrium policy, given by Lemma 1, does not depend on $D_i'(.)$ when $\sum_N S_i' = 0$, M's policy is the same whether it is set before or after investments, despite Proposition 3. Finally, when combining Lemmas 2 and 3 with Proposition 2, $\partial U_M / \partial r_i = 0$. This implies that M has no interest in influencing r_i, $i \in N$, and the deposit allocation described by Lemmas 1-3 continues to be an equilibrium. The proof that this must be true in all equilibria follows the same steps as before.

As a variant of the model, suppose the r_i's were not chosen by private investors but by governments. For $i = M$, this turns out to be irrelevant since, as noted, r_M is optimal from M's point of view. Also for $i \in N$, this change would not matter if government i took the price p as given, perhaps because the price had already been set by M at the policy stage. However, if i anticipates that r_i may affect the price, the first-order condition for r_i becomes:

$$k_i'(r_i^*) = \widetilde{B}_i'(y_i^* + r_i^*) - (y_i - x_i)\, \partial p / \partial r_i \ \forall i \in N.$$

Better technology reduces the fuel price ($\partial p / \partial r_i < 0$). The lower price is good for country $i \in N$ if it imports fuel but bad if it exports. Hence, importers invest more than exporters. If $(y_i - x_i)$ is very large, i may actually invest too much, compared to the social optimum, just as M would have done, according to Proposition 1. With a deposit market, however, $y_i = x_i$ and it does not matter whether i, at the investment stage, takes p as given or not. The first-best continues to be an equilibrium whether investments are private or public.

4.2. Multiple periods

A one-period model may well capture a dynamic world. In particular, suppose the environmental damage $H(.)$ is a function of cumulated emissions, no matter at which point in time they take place. Then, the first-best is still implemented by the equilibrium above: M only needs to buy and set aside certain deposits at the start of the game, and then let the market work out the allocation of consumption. If time is a dimension in this allocation, the equilibrium price path optimally allocates the remaining production and consumption over time.

Without a deposit market, however, difficulties arise. In addition to the inefficiencies already discussed, there will be intertemporal leakages. If M is expected to reduce its future consumption, the expected future price declines. This makes it more attractive for the nonparticipants to extract fuel now. This effect has been referred to as the "green paradox" by Sinn (2008), since a harsher environmental policy (in the future) can actually increase emissions (today). Clearly, the green paradox reduces the value of an anticipated demand-side policy.[20]

To illustrate this, suppose there are two periods, $t \in \{1, 2\}$, and let $\delta \in (0, 1)$ be the common discount factor. As before, the extraction costs are associated with the deposits. Thus, if $C_i(.)$ is i's extraction cost function, the cost of extracting $x_{i,1}$ units in period 1 is $C_i(x_{i,1})$, while the remaining cost of extracting $x_{i,2}$ in period 2 is $C_i(x_{i,1} + x_{i,2}) - C_i(x_{i,1})$. To capture the intuition that climate change is a long-term problem, let the harm $H(.)$ be experienced only in the second period. Since greenhouse gases have a long-lasting impact on the climate, suppose $H(.)$ is a function of cumulated emissions. When the prices in periods 1 and 2 are p_1 and p_2, the payoff for $i \in M \cup N$ is:

$$\begin{aligned} U_i &= B_{i,1}(y_{i,1}) - C_i(x_{i,1}) + p_1(x_{i,1} - y_{i,1}) \\ &\quad + \delta\left[B_{i,2}(y_{i,2}) - C_i(x_{i,1} + x_{i,2}) + C_i(x_{i,1}) + p_2(x_{i,2} - y_{i,2})\right] \\ &\quad - \delta H\left(\sum_{t\in\{1,2\}} \sum_{j\in M\cup N} x_{j,t}\right)\Upsilon_i, \end{aligned} \tag{4.2}$$

where the index-function $\Upsilon_i = 0$ for $i \in N$, and $\Upsilon_M = 1$.

If M can commit to future policies, the timing of the game is the following. In the first period, M sets $\{x_{M,1}, y_{M,1}, x_{M,2}, y_{M,2}\}$. Thereafter, the first-period fossil fuel market clears. Finally, the second-period market clears.

For given prices, the demand in country $i \in N$ is $y_{i,1} = D_{i,1}(p_1) \equiv B_{i,1}'^{-1}(p_1)$ and $y_{i,2} = D_{i,2}(p_2) \equiv B_{i,2}'^{-1}(p_2)$. In the second period, i's cumulated supply is given by $x_{i,1} + x_{i,2} = S_i(p_2) \equiv C_i'^{-1}(p_2)$. In the first period, i must consider whether to extract

[20] A similar effect is identified by Kremer and Morcom (2000), who show that an anticipated future crackdown on the illegal harvesting of ivory may raise current poaching.

a marginal deposit now or later. This leads to $x_{i,1} = S_i\left(\left(p_1 - \delta p_2\right)/\left(1-\delta\right)\right)$.[21] In each period, the market must clear, such that $I_t \equiv y_{M,t} - x_{M,t} = \sum_N \left(x_{i,t} - y_{i,t}\right) \forall t \in \{1,2\}$.

Anticipating all this, M's optimal policy for both periods are derived in the Appendix. Just as before, the sum of the taxes must equal the marginal environmental harm.

Proposition 4. *If M can commit, its second-period policies are given by:*

$$B'_{M,2}\left(y_{M,2}\right) = p_2 + \left(\frac{dp_2}{dI_2}S'\left(p_2\right)\right)H' + \frac{dp_1}{dI_2}\frac{I_1}{\delta} + \frac{dp_2}{dI_2}I_2; \tag{4.3}$$

$$C'_M\left(x_{M,1}+x_{M,2}\right) \ni p_2 - \left(1 - \frac{dp_2}{dI_2}S'\left(p_2\right)\right)H' + \frac{dp_1}{dI_2}\frac{I_1}{\delta} + \frac{dp_2}{dI_2}I_2, \tag{4.4}$$

where :

$$\frac{dp_2}{dI_2} = \frac{S'\left(\left[p_1-\delta p_2\right]/\left[1-\delta\right]\right) - \left(1-\delta\right)D'_1}{\left[S'\left(p_2\right) - D'_2\right]\left[S'\left(\left[p_1-\delta p_2\right]/\left[1-\delta\right]\right) - \left(1-\delta\right)D'_1\right] - \delta S'\left(\left[p_1-\delta p_2\right]/\left[1-\delta\right]\right)D'_1},$$

$$\frac{dp_1}{dI_2} = \frac{\delta S'\left(\left[p_1-\delta p_2\right]/\left[1-\delta\right]\right)}{\left[S'\left(p_2\right) - D'_2\right]\left[S'\left(\left[p_1-\delta p_2\right]/\left[1-\delta\right]\right) - \left(1-\delta\right)D'_1\right] - \delta S'\left(\left[p_1-\delta p_2\right]/\left[1-\delta\right]\right)D'_1}.$$

On the other hand, if M cannot commit to future policies, its second-period policy is given by Lemma 1, above. A comparison shows that the two policies are, in general, quite different. First, when committing to second-period policies, M would like to consider the effect on its terms of trade not only for the second period, but also for the first. Once the second period has arrived, this effect is sunk and M can ignore it. This implies that M's ideal tax policy is not time-consistent, even when there is no environmental harm.[22]

Second, even if we abstract from the terms of trade effects, M's preferred policy under commitment is generally different from the equilibrium policy when it cannot commit. Even if $I_1 = I_2 = 0$, (4.3)-(4.4) implies that M would prefer to commit to rely more on supply-side policies, and less on demand-side policies, than what it is going to find optimal in period 2 ((3.5)-(3.6)). By doing this, M minimizes the intertemporal consumption leakage and the problems of the green paradox, discussed above.[23] Unfortunately, if M cannot commit, this policy is not time-consistent.

[21] To see this, take a small deposit with marginal cost c. It is extracted in period 1 rather than period 2 if this gives a higher present discounted value of the profit: $p_1 - c \geq \delta\left(p_2 - c\right) \Rightarrow c \leq \left(p_1 - \delta p_2\right)/\left(1-\delta\right)$.

[22] This result is known from Newbery (1976) and the subsequent literature (surveyed by Karp and Newbery, 1993).

[23] If, instead, M commits to reduce its future supply, the future fossil fuel price increases, and non-participants find it optimal to extract less in period 1 (but, as before, more in period 2). Thus, while the intertemporal effect of the second-period policy increases consumption leakage, it does not increase extraction leakage.

Consider now a deposit market at the beginning of period 1. For the same reason as before, Lemma 2 continues to hold and $x_{M,t} = y_{M,t}$, $\forall t \in \{1, 2\}$. M purchases from country $i \in N$ the deposits that are most costly to extract. Thus, Lemma 3 continues to hold for the second period (i.e., for $p = p_2$). This does not imply that i's supply is inelastic in period 1, but it does become locally inelastic in period 2. When we substitute $S_i'(p_2) = 0$ in (4.3)-(4.4), it is clear that M relies entirely on supply-side policies in period 2 whether or not it can commit. M's policy is thus time consistent. As the Appendix shows, once the deposit market clears, M relies on supply-side policies also in the first period, and intertemporal efficiency is ensured.

Theorem 2 (iii). *With a deposit market in the beginning of the game, the first-best is implemented by M's equilibrium policies whether or not M can commit to future policies.*

M's policy is simple to implement once the deposit market clears. It can just set aside the costliest deposits and thereafter let the market clear, or it can set extraction taxes, $\tau_{x,t}$, $t \in \{1, 2\}$, high enough to make the marginal deposits unprofitable. As shown in the Appendix, these taxes should be Pigouvian:

$$\tau_{x,1}/\delta = \tau_{x,2} = H'(.) .$$

Note that the tax should be positive in both periods. If there were an extraction tax only in the second period, the private suppliers would prefer to extract in period 1 rather than in period 2, just to avoid paying this tax. This would generate the green paradox, discussed above, and the outcome would be dynamically inefficient. To avoid this, the present-discounted value of the tax should be the same across periods.

The reasoning above continues to hold if there are more than two periods. In either case, a deposit market at the beginning of the game implements the first-best. Things would be more complicated, however, if M not only cared about the aggregate emissions, but the time at which they took place. M may then have an incentive to trade deposits at the beginning of every period. Whether this would ensure efficiency would depend on the structure of the deposit market. For example, if M could influence the future price it would pay for deposits by extracting less today, it would distort its extraction path in order to influence its future terms-of-trade. For similar reasons, a rental market for the right to extract deposits may not guarantee the first-best, if the future rental price can be influenced by M's extraction path.

4.3. Heterogeneous fuels

The analysis above assumed that consuming one unit of fossil fuel created one unit of pollution. In reality, fuel types differ in their carbon content: natural gas pollutes less than oil which, in turn, pollutes less than coal. Oil fields themselves differ widely: exploiting Canadian oil sands pollutes more than extracting North-Sea oil, for instance.

The model can accommodate heterogeneous fuels both within and between countries. For a small deposit of size Δ, let c be its marginal production cost and e its marginal emission content. Thus, the cost and emissions from exploiting this deposit are $c \cdot \Delta$ and $e \cdot \Delta$. As before, the deposits belonging to $i \in N$ are ordered according to their extraction costs.[24] If country $i \in N$ supplies x_i units, its total emission is $E_i(x_i)$, where $E_i'(x_i)$ is the marginal emission content of a deposit located at x_i. If $E_i'(x_i)$ is increasing (decreasing), the fuel that is most costly to extract is most (least) polluting. Assume that $E_i'(.)$ is continuous at x_i if $C_i'(.)$ is continuous at x_i,[25] and that $E_i'(x_i) \geq \overline{e}$ for all i and x_i, for some $\overline{e} > 0$. If $i \in M \cup N$ supplies x_i units, the total emissions level is $\sum_{M \cup N} E_i(x_i)$, and the harm, experienced by M, is $H\left(\sum_{M \cup N} E_i(x_i)\right)$.

Optimally, marginal benefits should be equalized across countries and a marginal deposit should be extracted if and only if:

$$c + eH'(.) \leq B_j'(y_j) = B_i'(y_i) \, \forall i, j \in M \cup N. \quad (4.5)$$

To find the equilibrium, note that stage 3 has the same outcome as in Section 3.1. At stage 2, M sets policies taking into account leakages and their emission content.

[24] The deposits belonging to M are ordered according to $c + eH'(.)$, where $H'(.)$ is evaluated at the equilibrium pollution level. The reason is that M is always exploiting the deposits with the smallest $c + eH'(.)$.

[25] This requires that deposits having almost identical extraction costs also have similar emission content. This assumption saves a step in the proof.

Lemma 4. *M's equilibrium policy implements:*

$$B'_M(y_M) = p + \frac{\sum_N E'_i(x_i)\,S'_i(p)}{S'(p) - D'(p)} H' + \frac{y_M - x_M}{S'(p) - D'(p)} \tag{4.6}$$

$$C'_M(x_M) \ni p - \left(E'_M(x_M) - \frac{\sum_N E'_i(x_i)\,S'_i(p)}{S'(p) - D'(p)}\right) H' + \frac{y_M - x_M}{S'(p) - D'(p)} \tag{4.7}$$

Note that M focuses more on reducing its demand, and less on reducing its supply, if fuel abroad tends to be dirtier than domestic fuel, particularly if this is true for foreign countries with a very elastic supply function. Just as before, one can easily find taxes implementing this policy. If E'_M is much smaller than E'_i, M may find it optimal to subsidize domestic extraction ($\tau_x < 0$). This may be the case, for example, if the participants possess natural gas while the nonparticipants rely on coal. The lemma generalizes the result by Golombek et al. (1995), who extend the model by Hoel (1994) to allow for three types of fuel.

Although Lemma 4 describes M's best policy to cope with free-riding and leakages, the outcome is not first-best for a generic allocation of deposits. In addition to the inefficiencies discussed already, country $i \in N$ tends to exploit the wrong deposits. Since $i \in N$ does not internalize the environmental harm, it might exploit deposits that have higher emission contents and larger social costs than some other deposit that it find too costly to exploit. For this reason, a deposit market is even more important than before.

Suppose i consider to sell a marginal deposit to M. The condition under which both can benefit (replacing (3.7) in Theorem 1) is:

$$\max\{0, c + eH' - B'_M(y_M)\} + (x_i - y_i)\frac{\partial p}{\partial \Delta} > 0. \tag{4.8}$$

Theorem 2 (iv). *In every equilibrium of the deposit market, M's equilbrium policy (4.6)-(4.7) implements the first-best (4.5) even if fuels vary in their emission content.*

Just as before, Lemmas 2 and 3 continue to hold: Deposits are sold to importers and there is no trade in fuel in equilibrium. Because every marginal deposit is polluting at least $\overline{e} > 0$, M purchases every marginal deposit from $i \in N$, who ends up with a locally inelastic supply curve. Substituted in (4.6), marginal benefits are equalized across countries. Every deposit satisfying $c \in (B'_M - eH', p)$ is purchased (in line with (4.8)) and preserved (according to Lemma 4) by M. This implements the first-best, given by (4.5).

4.4. Shared harm and shared ownership

So far, I have assumed that nonparticipants do not experience any harm from pollution. This assumption may approximate reality if the nonparticipants' harm is only a small fraction of the total harm. Moreover, if signing an international agreement is necessary to overcome domestic resistance for a climate policy, the nonparticipants' harm would not affect the equilibrium derived above. However, the above equilibrium would no longer implement the first-best, since M would not internalize the nonparticipants' harm when deciding how many deposits to set aside.

While $H(.)$ measures the total harm, as before, let $H_i(.)$ measure the harm experienced by country i. Clearly, $H(.) \equiv \sum_{M \cup N} H_i(.)$. The optimal x_i^*s can be derived as before. Then, define:

$$\alpha_i \equiv H_i'\left(\sum x_i^*\right) / H'\left(\sum x_i^*\right).$$

Parameter $\alpha_i \in [0,1]$ measures i's marginal harm as a fraction of the total marginal harm at the optimal emission levels.

Oil companies often share the ownership of oil fields. Similarly, suppose that ownership of fossil fuel deposits can be shared by countries. If a country owns a certain fraction of a given deposit, and this deposit is exploited, then the country receives a share of the profit equal to its ownership-share.

Theorem 2 (v). *There exist an equilibrium in the deposit market where i owns α_i of every deposit satisfying:*

$$c \in \left(\rho - H'\left(\sum_N x_i^*\right), \rho\right), \ \rho \equiv B_i'(y_i^*) \, \forall i \in M \cup N. \tag{4.9}$$

This equilibrium implements the first-best.

Take a small deposit of size Δ with marginal extraction cost c satisfying (4.9). If exploited, i's benefit would be $\alpha_i [B_i'(y_i^*) - c - H'(.)] \Delta < 0$, and every i would thus prefer to not exploit such a deposit. This is socially optimal, since a deposit should only be exploited if $c \leq B_i'(y_i^*) - H'(\sum_N x_i^*)$. Deposits satisfying $c > B_i'(y_i^*)$ are not exploited by any owner. Hence, when i owns α_i of every deposit satisfying (4.9), the first-best is implemented, no matter whether the owners make decisions by unanimity or majority rule. Lemma 2 continues to hold and, besides setting aside deposits satisfying (4.9), further regulation is neither necessary nor desired. It follows that $B_i'(y_i^*)$ is equalized across countries.

The shares α_i constitute an equilibrium since no two owners would benefit by trading such a deposit share. If the consequence following such a transaction would be that a marginal deposit would be exploited, the new owner j would benefit $\alpha_i(p-c) - H_j'(.)$, which is less than the harm experienced by the previous owner i.

This is not a unique equilibrium when $|N| > 1$, however. If a deposit is owned and exploited by a single owner, it might not pay any individual country to step in and purchase a fraction of this deposit with the aim at preserving it. If the multiple potential owners cannot coordinate such a takeover, other equilibria exist which fail to implement the first-best.

4.5. The market structure for fuel

Even a nonparticipating country may have market power to influence the fuel price, and it generally has an interest in regulating its supply and demand in order to improve its terms-of-trade. Allowing for this would change the game somewhat - if there were no deposit market. For instance, suppose that country $o \in N$ has the power to set the fuel price at stage 3, while every $i \in N \backslash o$ takes the price as given at stage 3, just as before. If country o takes x_M and y_M as given (determined at stage 2), then it is easy to show that o's policy must satisfy:

$$B_o' = C_o' = p - \frac{x_o - y_o}{\sum_{N \backslash o} S_i'(p) - D_i'(p)} = p - \frac{\sum_{N \backslash o} D_i(p) - S_i(p) + y_M - x_M}{\sum_{N \backslash o} S_i'(p) - D_i'(p)}. \tag{4.10}$$

Thus, country o sets a higher price if it is a net exporter. This implies that if M consumes more or extracts less, the price increases, just as before. Condition (4.10) should be taken into account at stage 2, and M's optimal policy changes somewhat, compared to Lemma

1.

However, once the deposit market clears, Lemma 2 holds, $x_o = y_o$ and (4.10) can be written as $B_o' = C_o' = p$. This condition is exactly the same as before, and the fact that country o can set the price has then no impact on M's policy. It continues to be the case that every country is self-sufficient with fuel, in equilibrium, and it thus has no incentive to distort the world price by regulating its consumption, supply, or trade.

4.6. The market structure for deposits

Regarding the market for deposits, it has been assumed that the market clears where there exists no pair of countries, and no price, such that one country can sell a deposit to the other at that price and make both strictly better off. If this condition is violated, there are still gains from trade. The condition is actually stronger than necessary, since the proofs only consider trade between M and $i \in N$. I do not need to allow for trade between i and j, if $i, j \in N$.

Relying on this definition, there has been no need to specify how this equilibrium may be implemented. But there are several possibilities. A simple example is to suppose that country $i \in M \cup N$ can make a conditional take-it-or-leave-it offer to all the other countries, specifying a new allocation of deposits (thus, implicitly specifying a vector of transactions) and a vector of payments to be made. If every country can veto this proposal, the outcome gives Lemmas 2-3, and thus the above outcome.[26] This procedure is referred to as "conditional bids" by Segal (1999) and as "no free riding" by Joskow and Tirole (2000).[27] The price M must pay will obviously depend on the allocation of

[26] To see this, suppose that if there is no trade in the deposit market, country j gets utility $\overline{U}_j$. With a deposit market, j gets U_j, which depends on the allocation of deposits, minus q_j, the payment it must make. If $i \in M \cup N$ can make a take-it-or-leave-it offer to the rest, it maximizes $U_i + \sum_{M \cup N \backslash i} q_j$ s.t. $U_j - q_j \geq \overline{U}_j \; \forall j \in M \cup N \backslash i$. The constraints will certainly bind in equilibrium and i thus maximizes $U_i + \sum_{M \cup N \backslash i} \left(U_j - \overline{U}_j \right)$, and therefore $\sum_{M \cup N} U_j$, the aggregate surplus. Sufficient conditions for the maximum are given by Lemmas 2-3. In all equilibria of this game, $x_M = y_M$, but in some equilibria, $x_i \neq y_i$ for some $i \in N$. Thus, this game has equilibria that does not necessarily clear the market the way the equilibrium is defined, but Theorem 2 continues to hold, nevertheless (since it only requires $x_M = y_M$ and not $x_i = y_i \forall i \in N$). This implies that the definition of a market equilibrium, used above, is stronger than necessary.

[27] However, as these papers show, other market structures fail to implement the efficient equilibrium. For example, if M makes observable non-conditional take-it-or-leave-it offers to the other countries, then M may prefer to restrict trade in deposits below the efficient level in order to affect its terms-of-trade.

bargaining power. As illustrated in Section 3.5, M is likely to pay less if it has more bargaining power, if the deposits are privately owned and if there are just a few owners.

4.7. Participation

There is no consensus on how to model participation the most reasonable way. A common method (see the survey by Barrett, 2005), is to introduce a stage zero in the game, where every player first decides whether to participate. Otherwise, the game unfolds as described in Section 2. To simplify, take the symmetric example in Section 3, but let *every* country face the same marginal harm h from pollution. Let the total number of countries be $l \equiv |M \cup N|$. As before, suppose nonparticipating countries implement policies neither on demand nor supply. This might be reasonable if an international treaty is necessary in order to overcome domestic political resistance. In any case, the following results would not change substantially by relaxing this assumption.

This participation game tends to create a lot of free-riding and incentives to abstain, since abstaining does not affect whether other countries participate. Without a deposit market, each country faces the following trade-off: participating is costly since consumption and production declines from x' to x^* in Figure 3. On the other hand, every other participant reduces its own pollution by $-\partial x^*/\partial m = h/(a+c)$ units. As in Barrett (2005), the equilibrium number of participants is just 3!

Adding a deposit market can either raise or reduce participation. On the one hand, the participating members are always better off with a deposit market. Joining this coalition, moreover, reduces the pollution by $h/(a+c)$ units not only for the participants, but for every country. On the other hand, nonparticipants are also better off compared to the situation without a deposit market. The coalition is successful in reducing emissions from every country. Paying for this is costly, however, and by joining the coalition country i is expected to share these costs. Ultimately, whether participation is more or less attractive with a deposit market depends on the deposit market structure. Even if M can make take-it-or-leave-it offers, the price depends on whether it is dealing with symmetric countries or simply producers (as in the asymmetric example).

Proposition 5. *(i) Without a deposit market, $m = 3$. (ii) If M purchases deposits from symmetric countries, $m = 2$. (iii) If M purchases deposits directly from individual producers,*

$$\begin{aligned} m &= \max\left\{l, \left\lfloor \frac{2l(a+c)+a}{lc+2a} \right\rfloor\right\} \\ &= l \text{ if } a/c \geq l(l-2). \end{aligned}$$

The function $\lfloor x \rfloor$ calculates the largest integer weakly smaller than x.

If M makes take-it-or-leave-it offers to countries, it must pay each nonparticipating country the triangle $\alpha + \beta$ in Figure 3. This price is so high that the motivation to participate declines compared to the situation without a deposit market. If this is important, potential members would thus like to commit, before the first stage, to not use a deposit market later on. Such a decision is not time consistent, however. After the participation stage, M would always prefer to purchase deposits.

On the other hand, if M only needs to compensate the *producers* of fossil fuel, paying the area α suffices. This price is lower, making participation more attractive. If $a \approx c$, participation is always larger with a deposit market than without as long as $l > 4$. If $a/c \geq l(l-2)$, full participation is possible.

4.8. Domestic opposition and lobbying

A tough climate policy might be supported by citizens and environmentalists, but producers as well as consumers are harmed when introducing taxes on demand and supply. Deposit-owners are stuck and unable to move from one country to another, however, and this may reduce their political clout. Industries relying on energy, on the other hand, may credible threaten to move. Babiker (2005) shows that leakage can be much larger if firms can exit and enter.

Without a deposit market, such consumers can benefit a lot from moving from a participating country to a nonparticipant. In the example above, the price is $bhm/(a+c)$ units higher in M than in N. With a deposit market, however, the price is equalized across participants and nonparticipants. Consumers have then no incentive to move, and this reduce their political clout if lobbying against a climate treaty.

Moreover, the incentive to lobby against a climate treaty is much smaller when there is a deposit market.[28] If a country i joins, the coalition reduces supply further and the equilibrium price on fossil fuel increases by $bh/(a+c)$ in every country. This price increase is only a fraction $(1/m)$ of the price increase for i's consumers if i joined M and there were no deposit market.

In sum, with a market for deposits, industries relying on energy have less incentive to lobby against memberships in a climate treaty and they have, in any case, less credibility when threatening to move. Participation in a climate treaty is thus meeting less domestic resistance if there is a deposit market.

5. Conclusions and limitations

A climate coalition faces several dilemmas. Not only are nonparticipants polluting too much. If the coalition reduces its consumption of fossil fuel, the world price declines and nonparticipants consume more. By reducing its supply, nonparticipants extract more from their deposits. Furthermore, nonparticipants invest too little in renewable energy sources. In response, the coalition's best policy distorts trade and it is not time consistent.

This paper investigates whether trading fossil fuel deposits can mitigate these problems. As argued in the Introduction, the right to exploit deposits might be contractible even if Coaseian bargaining on pollution levels is impossible. Theorem 1 states that the coalition often benefits from purchasing and preserving deposits that are, in any case, costly to exploit. While such trade may harm third parties, Theorem 2 shows that, once the deposit market clears, the outcome is first-best. In equilibrium, the coalition purchases the right to exploit deposits that are costly or polluting to exploit. This eliminates the supply-side leakage, and the coalition implements its ideal policy simply by reducing its supply of fuel. There is no need to regulate trade or consumption, and there is thus no consumption leakage. The fossil fuel price is equalized across countries, inducing optimal investments in technology. The first-best is thus implemented, even if some countries do not participate in the coalition. These results strengthen the case for a policy focusing

[28] Analogously, Grossman and Helpman (1995) study industry groups lobbying for or against the participation in a free-trade area.

on reducing the supply of, rather than the demand of, fossil fuel - if the objective is to implement a cost-effective climate policy.

More generally, the result shows that efficiency can be obtained without Coaseian bargaining ex post, if crucial input factors are tradable ex ante. This insight can be applied to other contexts. For example, boycotting timber from tropical forests would decrease the world price and lead other countries to raise their demand. To prevent such leakage, a wiser strategy may be to purchase the forest or pay countries to let their forests remain. The recent emergence of REDD funds is thus consistent with the prediction of this paper.

The case for "buying coal" is developed in a benchmark model that abstracts from a number of practical difficulties. First, the emission from a deposit may depend on the extractor's carefulness (or method of extraction) as well as the deposit itself. If such carefulness is noncontractible, moral hazard arises with and without a deposit market. Second, a country may own unknown or potential deposits, and with some effort it can detect whether these deposits contain fossil fuel. Since the incentive to search for new deposits is stronger if the price of fuel is high, countries may search more if there is a deposit market than if there is not. The effort to search is then suboptimally high, since a nonparticipant does not internalize the environmental consequence if a new deposit is detected and exploited, or it may gain from selling such a deposit even if it is not exploited and thus have no social value. In principle, the climate coalition has an incentive to purchase potential deposits, or to pay others for not searching. If such contracts cannot be made, the possibility to search for new deposits would weaken the efficiency result above. Third, after selling a deposit located within its national boundary, a country may have a strong incentive to nationalize the deposit and recapture its value. If nationalization is a threat, the coalition may prefer to instead lease the deposit, and simply pay the owner for not exploiting it temporarily. Whether the right to exploit deposits is for sale or for rent, efficiency follows, in the one-period model. In a dynamic model, however, the parties may distort their policies in order to influence future rental prices. Future research should investigate the best role for deposit trading when these obstacles are taken into account.

6. Appendix

Proof of Lemma 1: Differentiating (3.2), (3.3), and (3.4) gives:

$$\left\{ \begin{array}{c} dx_i = S_i'(p)\, dp \ \forall i \in N \\ dy_i = D_i'(p)\, dp \ \forall i \in N \\ dx_M - dy_M = \sum_N (dy_i - dx_i) \end{array} \right\} \Rightarrow$$

$$\begin{aligned} \frac{dp}{dI} &= \frac{1}{S'(p) - D'(p)}, \\ \frac{dx_i}{dI} &= \frac{S_i'(p)}{S'(p) - D'(p)}, \\ \frac{dy_i}{dI} &= \frac{D_i'(p)}{S'(p) - D'(p)}. \end{aligned} \tag{6.1}$$

Maximizing U_M w.r.t. x_M and y_M s.t. (6.1) gives (3.5) as the first-order conditions. The second-order conditions hold if C_M and H are sufficiently convex, and they always hold in equilibrium.

To see this, note that the first-order conditions when maximizing w.r.t. x_M and p becomes:

$$\begin{aligned} B_M'(y_M) - C_M'(x_M) - H'(.) &= 0, \\ (B_M'(y_M) - p)\sum_N (S_i'(p) - D_i'(p)) - H'\sum_N S_i'(p) - (y_M - x_M) &= 0. \end{aligned}$$

The second-order conditions require that $\partial^2 U_M(x_M,p)/(\partial x_M)^2 \leq 0$, $\partial^2 U_M(x_M,p)/(\partial p)^2 \leq 0$ and $\left[\partial^2 U_M(x_M,p)/(\partial x_M)^2\right]\left[\partial^2 U_M(x_M,p)/(\partial p)^2\right] - \left[\partial^2 U_M(x_M,p)/\partial p \partial x_M\right]^2 \geq 0$. The first two conditions are, respectively:

$$B_M''(y_M) - C_M''(x_M) - H''(.) \leq 0,$$

$$\begin{aligned} (B_M'(y_M) - p)\sum_N (S_i''(p) - D_i''(p)) - 2\sum_N (S_i'(p) - D_i'(p)) \\ +B_M''(y_M)\left[\sum_N (S_i'(p) - D_i'(p))\right]^2 - H''(.)\left[\sum_N S_i'(p)\right]^2 \\ -H'(.)\sum_N S_i''(p) \leq 0 \end{aligned}.$$

Of the two conditions above, the first always hold. The second holds if H is sufficiently convex. However, once the deposit market clears ($x_i = y_i$), the second condition boils down to:

$$2\sum_N D_i'(p) + B_M''(y_M)\left[\sum_N D_i'(p)\right]^2 \leq 0,$$

which always hold.

The cross derivative is:

$$\frac{\partial^2 U_M(x_M,p)}{\partial p \partial x_M} = B''_M(y_M)\sum_N \left(S'_i(p) - D'_i(p)\right) - H''(.)\sum_N S'_i(p),$$

which is smaller if H is very convex. When the deposit market clears, this boils down to:

$$\frac{\partial^2 U_M(x_M,p)}{\partial p \partial x_M} = -B''_M(y_M)\sum_N 1/B''_i.$$

so the third condition (for the second-order condition to hold) becomes:

$$[B''_M - C''_M - H'']\left[2\sum_N D'_i(p) + B''_M(y_M)\left[\sum_N D'_i(p)\right]^2\right] - \left[B''_M(y_M)\sum_N D'_i\right]^2 \geq 0 \Rightarrow$$

$$[B''_M - C''_M - H'']\left[2\sum_N 1/B''_i + B''_M(y_M)\left[\sum_N 1/B''_i\right]^2\right] - \left[B''_M(y_M)\sum_N 1/B''_i\right]^2 \geq 0 \Rightarrow$$

$$-\left[2 + \sum_N B''_M/B''_i\right]\sum_N [C''_M + H'']/B''_i + 2\sum_N B''_M/B''_i \geq 0,$$

which always hold.

Proof of Theorem 1: Consider an equilibrium allocation of deposits giving cost functions $C_i(.)$ and equilibrium productions $x_i \forall i$, and $x_i = S_i(p) = C_i'^{-1}(p)\,\forall i \in N$. Take a small deposit of size Δ with a marginal exploitation cost $c < B'(y_M) - H'$, small enough to make the deposit profitable to exploit whether owned by i or M. If the deposit market clears, i cannot own such a deposit if M would value it more than i. If the right to exploit Δ is transferred from i to M, i's utility becomes:

$$U_i = \max_{x_i,y_i} B_i(y_i) - C_i(x_i) + c\Delta - p(y_i - x_i) - p\Delta. \tag{6.2}$$

Whether or not $C'_i(.)$ is singular at x_i, we can use the envelope theorem to differentiate (6.2). This gives:

$$\frac{dU_i}{d\Delta} = c - p - (y_i - x_i)\frac{dp}{d\Delta}. \tag{6.3}$$

After the transaction, M's utility becomes:

$$U_M = \max_{p,x_M} B_M(y_M) - C_M(x_M) - c\Delta - H(x_M + \Delta + S(p) - \Delta) + p(x_M + \Delta - y_M), \tag{6.4}$$

where I let M maximize w.r.t. p and x_M instead of, for example, y_M and x_M. In any case, (3.2)-(3.4) must be satisfied, implying

$$y_M = x_M + \Delta + S(p) - \Delta - D(p),$$

thus a function of p and x_M but not Δ. Using the envelope theorem when differentiating (6.4), we get simply

$$\frac{dU_M}{d\Delta} = p - c. \tag{6.5}$$

The sum of utilities for M and i is thus $(x_i - y_i)\, dp/d\Delta$, while for the society as a whole, one should take into account j's benefit $(x_j - y_j)\, dp/d\Delta$, $j \in N \backslash i$. Note that $dp/d\Delta > 0$ follows when differentiating U_M in (6.4) w.r.t. p and the second-order condition holds.

Next, consider a deposit $c \in (B'(y_M) - H', p)$, such that M would not exploit it. After the transaction, M's utility becomes:

$$\begin{aligned} U_M &= \max_{p, x_M} B_M(y_M) - C_M(x_M) - H(x_M + S(p) - \Delta) + p(x_M + \Delta - y_M), \qquad (6.6) \\ &\quad \text{where } y_M = x_M + S(p) - \Delta - D(p). \end{aligned}$$

Using the envelope theorem when differentiating (6.6), we get simply,

$$\frac{dU_M}{d\Delta} = -B'_M(y_M) + H' + p.$$

The change in the utility of i is (6.3), as before. Thus, i and M jointly benefit if $c - B'_M(y_M) + H' - (y_i - x_i)\, dp/d\Delta > 0$. For the world as a whole, one should also take into account j's benefit $(x_j - y_j)\, dp/d\Delta$, $j \in N \backslash i$.

Proof of Lemma 2: If $i \in N$ is an exporter, in equilibrium i will sell any profitable deposit to M, according to Theorem 1. Thus, in equilibrium $y_i \geq x_i \forall i \in N \Rightarrow x_M - y_M \geq 0$. If i is an importer, then if i sells a deposit with marginal cost $c < B'_M(y_M) - H'$ to M, the sum of U_i and U_M declines, according to Theorem 1. Thus, they will both benefit from the reverse transaction. Such a transaction is always possible, since M is producing $x_M \geq y_M > 0$ only using deposits satisfying $c < B'_M(y_M) - H'$. Such trade will take place as long as $y_i < x_i$. In equilibrium, therefore, $y_i = x_i \forall i \in N$.

Proof of Lemma 3: To prove the lemma by contradiction, suppose that, for some $i \in N$, $C'_i(x_i)$ were singular at the equilibrium deposit allocation and x_i. Then $C'_i(x_i) = B'_i(y_i) \forall i \in N$, and there exists some deposit of size $\Delta > 0$ with marginal cost $c \leq C'_i(x_i) = B'_i(y_i) = p$ and

$$c > p - H'(.)\left(1 - \frac{S'(p)}{S'(p) - D'(p)}\right). \tag{6.7}$$

If the right to exploit this deposit were transferred from i to M, i's utility gain would be (6.3), as before. But M would not produce from this deposit when $x_M = y_M$, according to Lemma 1, and after the transaction M's utility would be:

$$U_M = \max_{p, x_M} B_M(y_M) - C_M(x_M) - H(x_M + S(p) - \Delta) - p(y_M - x_M), \tag{6.8}$$

where the variables must satisfy (3.2)-(3.4), implying

$$y_M = x_M + S(p) - \Delta - D(p),$$

since i's supply is reduced by Δ relative to the initial $S_i(p)$. Using the envelope theorem when differentiating (6.8), we get

$$\frac{dU_M}{d\Delta} = -B'_M(.) + H'(.) + p. \tag{6.9}$$

Substituting $y_i = x_i$, the sum of (6.3) and (6.9) is

$$-B'_M(.) + H'(.) + c > -B'_M(.) + p + H'(.) \frac{S(p)}{S'(p) - D'(p)} = 0,$$

where I first used (6.7) and then Lemma 1 and 2. Since the total gain is strictly positive, there exist some price which makes both i and M better off following the transaction, implying that the initial allocation cannot be an equilibrium. It follows that for every $i \in N$, $C'_i(x_i)$ is nonsingular and, hence, $S'_i(p) = 0$.

It is possible that $\lim_{\epsilon \downarrow 0} S'_i(p+\epsilon) > 0$ but we must still have $B'_i(y_i) = B'_M(y_M)$ since, if $B'_M(y_M) < p = B'_i(y_i)$, M would strictly benefit by increasing y_M while simultaneously obtaining i's deposits with marginal cost $c > p$ (such that i would not increase its production following the increase in y_M). Since neither p nor unused deposits matter for $i \in N$ when $x_i = y_i$, i would be indifferent to such a transaction.

Proof of Proposition 2: (i) Note that $\partial U_j / \partial r_i = (x_j - y_j) \partial p / \partial r_i$ if $i, j \in N$, $i \neq j$, while $\partial U_i / \partial r_i = p + (x_j - y_j) \partial p / \partial r_i$ if $i \in N$. Since

$$\begin{aligned} U_M &= \max_{x_M, y_M, r_M} \widetilde{B}_M(y_M + r_M) - C_M(x_M) - H(x_M + S(p)) - p(y_M - x_M), \\ \frac{\partial U_M}{\partial r_i} &= [-H'(.) S'(p) - (y_M - x_M)] \frac{\partial p}{\partial r_i} \forall i \in N \Rightarrow \\ &\sum_{j \in M \cup N} \frac{\partial U_j}{\partial r_i} = p - H'(.) S'(p) \frac{\partial p}{\partial r_i}. \end{aligned} \tag{6.10}$$

By differentiating the first-order conditions (as in the proof of Lemma 1), we find $\partial p / \partial r_i = -1 / \sum_N [S'_j(p) - 1/B''_j(p)] < 0$ for pre-investment policies, while after the investment stage, $\partial p / \partial r_i < 0$ follows from the second-order condition when maximizing U_M w.r.t. p. Thus, if $S'(p) > 0$, socially optimal investments are given by $k'_i(r^*_i) = p - H'(.) S'(p) \partial p / \partial r_i > p = k'_i(r_i)$, so the equilibrium investment r_i is strictly smaller than the optimal r^*_i. (ii) At the policy stage, it must hold for M in (6.10) that $\partial p / \partial r_i = -1 / \sum_N [S'_j(p) - 1/B''_j(p)]$, whether x_M and y_M are sunk or yet to be optimally chosen. Substituting in (6.10) concludes the proof. Alternatively, for post-investment policies, it follows from the envelope theorem (when maximizing U_M w.r.t. x_M and p) that $\partial U_M / \partial r_i = \widetilde{B}'_M - p$, which can be written as (4.1), given (3.5).

Proof of Proposition 3: Lemma 1 continues to hold given the demand function $D_i(p)$ and the supply function $S_i(p)$.When r_i is sunk, demand is given by:

$$y_i = D_i(p) = \widetilde{B}'^{-1}_i(p) - r_i \Rightarrow \partial y_i / \partial p = D'_i(p) = 1 / \left(\widetilde{B}'^{-1}_i\right)'(p) = 1 / \widetilde{B}''_i(y_i + r_i).$$

Suppose now that r_i is decided after M's policy is set. The first-order condition for r_i, $i \in N$, is $p = k_i'(r_i)$. Differentiating this, we get $dr_i/dp = 1/k_i''(r_i)$. Thus, demand is now given by

$$\begin{aligned} D_i(p) &= y_i = \widetilde{B}_i'^{-1}(p) - r_i \Rightarrow \\ D_i'(p) &= \partial y_i/\partial p = \left(\widetilde{B}_i'^{-1}\right)'(p) - 1/k_i''(r_i) = 1/\widetilde{B}_i''(y_i + r_i) - 1/k_i''(r_i). \end{aligned}$$

The proofs below for Lemmas 1-4 permit heterogeneous fuels, as discussed in Section 4.3. Lemmas 1-3 are obtained by setting $E_i(x_i) = x_i$.

Proof of Lemma 1' and 4: Differentiating (3.2), (3.3), and (3.4) gives:

$$\left\{ \begin{array}{c} dx_i = S_i'(p)\,dp\ \forall i \in N \\ dy_i = D_i'(p)\,dp\ \forall i \in N \\ dx_M - dy_M = \sum_{i\in N}(dy_i - dx_i) \end{array} \right\} \Rightarrow$$

$$\begin{aligned} \frac{dp}{dx_M - dy_M} &= \frac{-1}{\sum_{i\in N}(S_i'(p) - D_i'(p))}, \qquad (6.11) \\ \frac{dx_i}{dx_M - dy_M} &= \frac{-S_i'(p)}{\sum_{i\in N}(S_i'(p) - D_i'(p))}, \\ \frac{dy_i}{dx_M - dy_M} &= \frac{-D_i'(p)}{\sum_{i\in N}(S_i'(p) - D_i'(p))}. \end{aligned}$$

M's problem is:

$$\max_{x_M, y_M} B_M(y_M) - C_M(x_M) - H\left(E_M(x_M) + \sum_N E_i(S_i(p))\right) + p(x_M - y_M),$$

giving the first-order conditions for x_M and y_M:

$$\begin{aligned} -C_M'(x_M) - H'(.)\left[E_M'(.) + \sum_N E_i'(.)\,S_i'(p)\frac{\partial p}{\partial x_M}\right] + p + (x_M - y_M)\frac{\partial p}{\partial x_M} &= 0, \\ B_M'(y_M) - H'(.)\left[\sum_N E_i'(.)\,S_i'(p)\frac{\partial p}{\partial y_M}\right] - p + (x_M - y_M)\frac{\partial p}{\partial y_M} &= 0. \end{aligned}$$

Substituting $\partial p/\partial y_M = -\partial p/\partial x_M = 1/\left[\sum_{i\in N}(S_i'(p) - D_i'(p))\right]$ from (6.11) gives (4.6)-(4.7).

Proof of Lemma 2': Consider an equilibrium allocation of deposits giving cost functions $C_i(.)$ and equilibrium productions $x_i \forall i$, and $x_i = S_i(p) = C_i'^{-1}(p)\,\forall i \in N$. Take a small deposit of size Δ with a marginal exploitation cost c and emission content e, both small enough to make the deposit profitable to exploit whether owned by i or M. If the right to exploit Δ is transferred from i to M, i's utility becomes:

$$U_i = \max_{x_i, y_i} B_i(y_i) - C_i(x_i) + c\Delta - p(y_i - x_i) - p\Delta. \qquad (6.12)$$

Whether or not $C'(.)$ is singular at x_i, we can use the envelope theorem to differentiate (6.12). This gives:

$$\frac{dU_i}{d\Delta} = c - p - (y_i - x_i)\frac{dp}{d\Delta}. \tag{6.13}$$

After the transaction, M's utility becomes:

$$\begin{aligned} U_M &= \max_{p,x_M} B_M(y_M) - C_M(x_M) - c\Delta + p(x_M + \Delta - y_M) \\ &\quad -H\left(E_M(x_M) + e\Delta + \sum_N E_i(S_i(p)) - e\Delta\right), \end{aligned} \tag{6.14}$$

where I let M maximize w.r.t. p and x_M instead of, for example, y_M and x_M. In any case, (3.2)-(3.4) must be satisfied, implying

$$y_M = x_M + \Delta + \sum_N S_i(p) - \Delta - \sum_N D_i(p),$$

thus a function of p and x_M but not Δ. Using the envelope theorem when differentiating (6.14), we get simply

$$\frac{dU_M}{d\Delta} = p - c. \tag{6.15}$$

Note that the first-order condition of (6.14) w.r.t. p is:

$$(B_M'(.) - p)\left[\sum_N S_i'(p) - \sum_N D_i'(p)\right] - H'(\cdot)\left(\sum_N E_i'(S_i'(p))\right) + (x_M + \Delta - y_M) = 0. \tag{6.16}$$

Since (6.16) must decrease in p for the second-order condition to be satisfied, and since (6.16) is increasing in Δ, it follows that $dp/d\Delta > 0$.

Thus, if $y_i < x_i$, the sum of (6.13) and (6.15) is positive, implying that there exist some price which makes both i and M better off following the transaction. If $y_i > x$, both i and M could be better off by the reverse transaction. *QED*

Proof of Lemma 3': The prove the lemma by contradiction, suppose that, for some $i \in N$, $C_i'(x_i)$ were singular at the equilibrium deposit allocation and x_i. Then $E_i'(.)$ is continuous at x_i, and there are generically two possibilities.

(i) If

$$p - C_i'(x_i) < H'(.)\left(E_i'(x_i) - \frac{\sum_N E_j'(x_j)\, S_j'(p)}{\sum_N \left(S_j'(p) - D_j'(p)\right)}\right),$$

then i owns a deposit of size Δ with marginal cost c and emission factor $e\Delta$ such that $p > c$ but

$$p - c < H'(.)\left(e - \frac{\sum_N E_j'(x_j)\, S_j'(p)}{\sum_N \left(S_j'(p) - D_j'(p)\right)}\right). \tag{6.17}$$

If the right to exploit this deposit were transferred from i to M, i's utility gain would be (6.13), as before. But M would not produce from this deposit when $x_i = y_i$, according to

(4.7), and after the transaction M's utility would be:

$$U_M = \max_{p,x_M} B_M(y_M) - C_M(x_M) - H\left(E_M(x_M) + \sum_N E_i(S_i(p)) - e\Delta\right) - p(y_M - x_M), \tag{6.18}$$

where the variables must satisfy (3.2)-(3.4), implying

$$y_M = x_M + \sum_N S_i(p) - \Delta - \sum_N D_i(p),$$

since i's supply is reduced by Δ relative to the initial $S_i(p)$. Using the envelope theorem when differentiating (6.18), we get

$$\frac{dU_M}{d\Delta} = -B_M'(.) + eH'(.) + p. \tag{6.19}$$

Substituting $y_i = x_i$, the sum of (6.13) and (6.19) is

$$-B_M'(.) + eH'(.) + c > -B_M'(.) + p + H'(.)\frac{\sum_N E_j'(x_j)S_j'(p)}{\sum_N \left(S_j'(p) - D_j'(p)\right)} = 0,$$

where I first used (6.17) and then Lemma 1 and 2. Since the total gain is strictly positive, there exist some price which makes both i and M better off following the transaction, implying that the initial allocation cannot be an equilibrium.

(ii) If instead

$$p - C_i'(x_i) > H'(.)\left(E_i'(x_i) - \frac{\sum_N E_j'(x_j)S_j'(p)}{\sum_N \left(S_j'(p) - D_j'(p)\right)}\right),$$

then i owns a deposit of size Δ with marginal cost c and emission factor $e\Delta$ such that $p < c$ but

$$p - c > H'(.)\left(e - \frac{\sum_N E_j'(x_j)S_j'(p)}{\sum_N \left(S_j'(p) - D_j'(p)\right)}\right). \tag{6.20}$$

The deposit is not exploited by i and i is indifferent to transferring it to M. If M owned it, M would exploit it according to (4.7) and thus benefit from obtaining it. Thus, the initial allocation cannot be an equilibrium.

It is possible that $\lim_{\epsilon\downarrow 0} S_i'(p+\epsilon) > 0$ but we must still have $B_i'(y_i) = B_M'(y_M)$ since, if $B_M'(y_M) < p = B_i'(y_i)$, M would strictly benefit by increasing y_M while simultaneously obtaining i's deposits with marginal cost $c > p$ (such that i would not increase its production following the increase in y_M). Since neither p nor unused deposits matter for $i \in N$ when $x_i = y_i$, i would be indifferent to such a transaction.

Proof of Proposition 4: The first-order conditions for $i \in N$ are, together with the budget constraints:

$$\begin{aligned} y_{i,t} &= D_{i,t}\left(p_t\right), \\ x_{i,1}+x_{i,2} &= S_i\left(p_2\right), \\ x_{i,1} &= S_i\left(\frac{p_1-\delta p_2}{1-\delta}\right), \\ \sum_N\left(x_{i,1}-y_{i,1}\right) &= I_1 \equiv y_{M,1}-x_{M,1}, \\ \sum_N\left(y_{i,2}-x_{i,2}\right) &= I_2 \equiv y_{M,2}-x_{M,2}. \end{aligned}$$

This system of $4n+2$ equations pins down p_t, $x_{i,t}$ and $y_{i,t}$ for all $i \in N$, $t \in \{1,2\}$ as a function of I_1 and I_2. Differentiating these equations gives:

$$\begin{aligned} dy_{i,t} &= dp_t D'_{i,t}, \\ dx_{i,1}+dx_{i,2} &= dp_2 S'_i\left(p_2\right), \\ dx_{i,1} &= \left(\frac{dp_1-\delta dp_2}{1-\delta}\right) S'_i\left(\frac{p_1-\delta p_2}{1-\delta}\right), \\ \sum_N\left(dx_{i,1}-dy_{i,1}\right) &= dI_1, \\ \sum_N\left(dx_{i,2}-dy_{i,2}\right) &= dI_2. \end{aligned}$$

By substitution, we get:

$$\begin{aligned} \sum_N\left(\left(\frac{dp_1-\delta dp_2}{1-\delta}\right) S'_i\left(\frac{p_1-\delta p_2}{1-\delta}\right)-dp_1 D'_{i,1}\right) &= dI_1, \\ \sum_N\left(dp_2 S'_i\left(p_2\right)-\left(\frac{dp_1-\delta dp_2}{1-\delta}\right) S'_i\left(\frac{p_1-\delta p_2}{1-\delta}\right)-dp_2 D'_{i,2}\right) &= dI_2. \end{aligned}$$

Set $S'_1 \equiv \sum_N S'_i\left(\left[p_1-\delta p_2\right]/\left[1-\delta\right]\right)$, $S'_2 \equiv \sum_N S'_i\left(p_2\right)$, $D'_1 \equiv \sum_N D'_{i,1}\left(p_1\right)$, $D'_2 \equiv \sum_N D'_{i,2}\left(p_2\right)$, and solve for dp_1 and dp_2:

$$\begin{aligned} dp_2 &= \frac{dI_2+dI_1 S'_1/\left(S'_1-D'_1\left(1-\delta\right)\right)}{S'_2-D'_2-\delta D'_1 S'_1/\left(S'_1-D'_1\left(1-\delta\right)\right)}, \\ dp_1 &= \frac{dI_1\left(1-\delta\right)}{S'_1-D'_1\left(1-\delta\right)}+\delta\frac{S'_1}{S'_1-D'_1\left(1-\delta\right)}\left(\frac{dI_2+dI_1 S'_1/\left(S'_1-D'_1\left(1-\delta\right)\right)}{S'_2-D'_2-\delta D'_1 S'_1/\left(S'_1-D'_1\left(1-\delta\right)\right)}\right). \end{aligned}$$

At the policy-stage, M chooses $\{x_{M,1}, y_{M,1}, x_{M,2}, y_{M,2}\}$ to maximize (4.2) for $i = M$. The first-order conditions for $x_{M,2}$ and $y_{M,2}$ give:

$$\begin{aligned} -\left(1-S'_2\frac{dp_2}{dI_2}\right)H'+p_2+\frac{dp_1}{dI_2}\frac{I_1}{\delta}+\frac{dp_2}{dI_2}I_2 &\in C'_M\left(x_{M,1}+x_{M,2}\right), \quad (6.21) \\ -\left(S'_2\frac{dp_2}{dI_2}\right)H'+B'_{M,2}-p_2-\frac{dp_1}{dI_2}\frac{I_1}{\delta}-\frac{dp_2}{dI_2}I_2 &= 0, \end{aligned}$$

This policy can be implemented by, for example, the following taxes on production and consumption:

$$\begin{aligned}\tau_{x,2} &= \left(1 - S_2' \frac{dp_2}{dI_2}\right) H' - \frac{dp_1}{dI_2}\frac{I_1}{\delta} - \frac{dp_2}{dI_2} I_2, \\ \tau_{y,2} &= \left(S_2' \frac{dp_2}{dI_2}\right) H' + \frac{dp_1}{dI_2}\frac{I_1}{\delta} + \frac{dp_2}{dI_2} I_2.\end{aligned}$$

The first-order conditions for the first period gives (we can ignore the effect of $x_{M,1}$ on $x_{M,1} + x_{M,2}$ using the envelope theorem since the f.o.c. w.r.t. $x_{M,2}$ is equivalent to the f.o.c. w.r.t. $x_{M,1} + x_{M,2}$):

$$\begin{aligned}-\delta\left(\frac{dp_2}{dI_2} - \frac{dp_2}{dI_1}\right) S_2' H' - (1-\delta)\, C_M'(x_{M,1}) + p_1 - \delta p_2 & \\ + \frac{dp_1}{dI_1} I_1 + \delta \frac{dp_2}{dI_1} I_2 - \frac{dp_1}{dI_2} I_1 - \delta \frac{dp_2}{dI_2} I_2 &= 0, \\ -\delta\left(\frac{dp_2}{dI_1} S_2'\right) H' + B_{M,1}' - p_1 - \frac{dp_1}{dI_1} I_1 - \delta \frac{dp_2}{dI_1} I_2 &= 0.\end{aligned} \tag{6.22}$$

For a given set of taxes, $x_{M,1}$ would be given by

$$p_1 - C_M'(x_{M,1}) - \tau_{x,1} = \delta\left(p_2 - C_M'(x_{M,1}) - \tau_{x,2}\right).$$

By combining the last five equations, M's first-period policy can be implemented by:

$$\begin{aligned}\tau_{x,1} &= \delta\left(1 - \frac{dp_2}{dI_1} S_2'\right) H' - \frac{dp_1}{dI_1} I_1 - \delta \frac{dp_2}{dI_1} I_2, \\ \tau_{y,1} &= \delta\left(\frac{dp_2}{dI_1} S_2'\right) H' + \frac{dp_1}{dI_1} I_1 + \delta \frac{dp_2}{dI_1} I_2.\end{aligned}$$

Note that $\tau_{x,1}/\delta > \tau_{x,2}$ if $I_1 = I_2 = 0 < S_2'$. The reason is that i's aggregate production is increasing in p_2 which, in turn, increases more in $\tau_{x,2}$ than in $\tau_{x,1}$.

Proof of Theorem 2 (iii): Lemmas 2-3 hold for the same reasons as before and their proofs are thus omitted. Substituted in Proposition 4, the second-period policies remain the same whether or not M can commit to future policies. In either case, M relies only on supply-side politics in the second period and $B_{M,2}' = p_2 = B_{i,2}' \forall i \in N$. In the first period, M's policy is given by (6.22) if M can commit. If M cannot commit to future policies, M may also want to take into account how first period policies affect second period policies. But since the second-period policy, given by Lemma 1, is identical to M's ideal policy (described by Proposition 4) if M can commit and $I_1 = I_2 = S_2' = 0$, this effect can be ignored (using the envelope theorem). In either case, (6.22) describes M's optimal policy for the first period. Substituting $I_1 = I_2 = S_2' = 0$ in (6.22) implies $B_{M,1}' = p_1 = B_{i,1}'$. M extracts the optimal amount since (6.21) implies $p_2 + H' \in C_M'(x_{M,1} + x_{M,2})$, and $i \in N$ extracts the optimal amount by Theorem 1. In addition, dynamic efficiency requires $x_{i,1} = C_i'^{-1}\left(\left[B_{j,1}' - \delta B_{j,2}'\right] / [1-\delta]\right)$. It is easily checked that this is satisfied for all $i \in M \cup N$.

Proof of Proposition 5: (i) is in line with previous results and its proof thus omitted. (ii): The environmental benefit of joining is $h^2 l/(a+c)$ since every country is reducing pollution by $h/(a+c)$ compared to when i did not join. But participation implies that i looses the consumer and producer surplus $h^2 m^2/2(a+c)$. In addition, i must share $1/m$ of the expenditures when compensating each of the $n = l - m$ nonparticipating producers $h^2 m^2/2(a+c)$. Summing up, participation is beneficial if

$$\frac{h^2}{a+c}\left[l - \frac{m^2}{2} - \frac{m(l-m)}{2}\right] \geq 0 \Rightarrow m \leq 2.$$

Proof for (iii): The environmental benefit of joining is $h^2 l/(a+c)$, since every country is reducing pollution by $h/(a+c)$ compared to when i did not join. But while i without participating would only loose the consumer surplus $ah^2(m-1)^2/2(a+c)^2$, by participation it looses its consumer and producer surplus $h^2 m^2/2(a+c)$. In addition, i must share $1/m$ of the expenditures when compensating each of the $l-m$ nonparticipating producers $ch^2 m^2/2(a+c)^2$. Summing up, and defining $\gamma \equiv a/(a+c)$, participation is beneficial if

$$\frac{h^2}{a+c}\left[l + \frac{\gamma}{2}(m-1)^2 - \frac{m^2}{2} - \frac{(1-\gamma)m(l-m)}{2}\right] \geq 0 \Rightarrow \frac{2l+\gamma}{l(1-\gamma)+2\gamma} \geq m.$$

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