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Buy Coal! A Case for Supply-Side Environmental Policy

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Free-riding is at the core of environmental problems. If a climate coalition reduces its emissions, world prices change and nonparticipants typically emit more; they may also extract the dirtiest type of fossil fuel and invest too little in green technology. The coalition's second-best policy distorts trade and is not time consistent. However, suppose that the countries can trade the rights to exploit fossil-fuel deposits: As soon as the market clears, the above-mentioned problems vanish and the first-best is implemented. In short, the coalition's best policy is to simply buy foreign deposits and conserve them.

I. Introduction

The traditional approach to environmental policy is to focus on the demand side: for example, pollution permits may be allocated or the consumption of fossil fuel might be taxed. The purpose of this paper is to demonstrate the benefits of focusing on the supply side, including the supply from foreign countries.

To appreciate the result, note that environmental policy is seldom efficient when some polluters do not cooperate. Although climate change is a global public bad, many countries are unlikely to ever join a legally binding climate treaty. Only 37 countries committed to binding

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targets under the Kyoto Protocol, and the effort to raise participation for a replacement treaty is still ongoing. Nonparticipants are likely to emit too much CO_2, but 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 emissions and may motivate them to set tariffs or border taxes, perhaps causing a trade war. Frankel (2009, 507) concludes that "it is essential to find ways to address concerns about competitiveness and leakage."[2]

To illustrate these problems, I first consider a model in which a coalition of countries is harmed by the global consumption of fossil fuel. Countries outside of the coalition are naturally emitting too much compared to the optimum. In addition, if the coalition reduces its demand for fossil fuel, the world price for fuel declines and so the nonparticipating countries consume more. If the coalition shrinks its supply of fossil fuel, the nonparticipants increase their supply. If countries can invest in renewable energy sources, nonparticipants invest too little compared to the first-best levels. For the coalition, it is only a second-best policy to regulate its own consumption, production, and trade. Furthermore, the coalition prefers to set policies so as to influence its terms of trade as well as the climate. Thus, the equilibrium policy distorts trade and is far from efficient.

The novelty in my analysis is that I allow countries to trade fossil-fuel deposits before climate and trade policies are set. A deposit here refers to a physical and geographical area that may contain fossil fuel such as coal, oil, or gas. A party that purchases a deposit, or the right to extract

[1] See the surveys in Rauscher (1997), IPCC (2007), and Frankel (2009). 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. For the countries signing the Kyoto Protocol, Böhringer and Löschel (2002, 152) estimate leakage to have increased from 22 to 28 percent when the United States dropped out. Babiker (2005) takes a long-term perspective by allowing firms to enter and exit and finds that leakage can be up to 130 percent.

[2] Before the 2009 climate negotiations in Copenhagen, the *Financial Times* wrote about carbon leakage that "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" (December 11, 2009); but "the danger is that arguments over border taxes could make an agreement even more difficult to negotiate" (November 5, 2009), and it is an "easy way to start a trade war" (December 9, 2009).

from a deposit, can decide whether or not to exploit it. Since such a bilateral transaction may alter the world price for fossil fuel, third parties can benefit or lose. Nevertheless, once the market for deposits clears, all the above-mentioned problems vanish and the first-best outcome is implemented.

In equilibrium, the coalition finds it beneficial to purchase the right to exploit the foreign fossil-fuel deposits that are most costly to exploit. Since these deposits would generate little profit if exploited, the owner is willing to sell them rather cheaply. As a side effect, the selling country's supply curve becomes a step function and its supply becomes locally inelastic. The coalition can then reduce its own supply marginally without fearing that nonparticipants will increase theirs. Without supply-side leakage, the coalition benefits from relying exclusively on supply-side policies and does not use demand-side policies that would have caused leakage. Consequently, the consumption price is equalized across countries, as are the marginal benefits from consumption. All allocations, including investments in technology, become efficient. The policy lesson is that purchasing fossil-fuel deposits, with the intention of preserving them, may be the best possible climate policy.

After a simple illustration, I describe my contribution to the literature before explaining that the policy is practical and has alternative applications. The basic model is described in Section II and analyzed in Section III. Section IV introduces multiple periods, investments in green technology, heterogeneous fuels, and other extensions. Conclusions and limitations are discussed in Section V, and the Appendix contains the proofs omitted from the text.

A. *An Example*

The outcome is particularly simple if the marginal benefits (B') and costs (C_0') are initially linear and identical for every country. With no environmental policy, every country consumes and supplies x' and the equilibrium fuel price is p_0, as shown in figure 1. In contrast, when a coalition experiences the marginal harm H' from emissions, then the first-best level for consumption and production is $x^* < x'$. But if the coalition reduces its own consumption, the world price decreases and other countries consume more. If the coalition reduces its supply of fossil fuel, the world price rises and other countries increase their supply. For the coalition, the best combined policy, without a deposit market, is to reduce both production and consumption to x^*, it turns out. Nonparticipating countries continue to consume and produce x', and the social loss is measured by the area $\alpha + \beta$ for every one of them.

With a deposit market, the coalition purchases foreign deposits with marginal extraction costs between p_S and p_B. The profit from exploiting

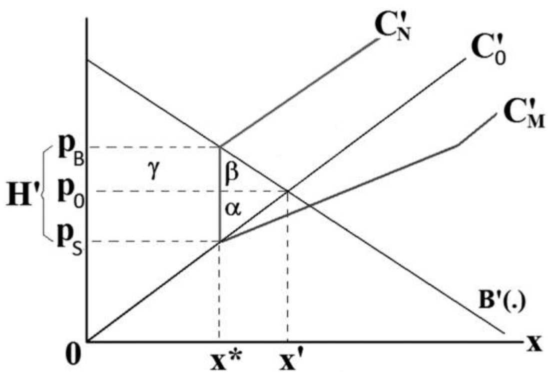

FIG. 1.—The coalition purchases the marginal

these deposits is smaller than the coalition's harm. After such trade, the nonparticipants' supply curve shifts to C'_N and the coalition's supply curve shifts to C'_M. Since the foreign supply becomes locally inelastic, the coalition can simply regulate its supply to x^* without fearing supply-side leakage. With this simple supply-side policy, the consumption price becomes p_B in every country, and the first-best is implemented without the need for any further regulation. I return to this example in Section IV.F.

B. *Literature and Contribution*

The Coase theorem.—By referring to several examples, Coase (1960) argued that parties that harm each other have incentives to negotiate and internalize these externalities. Under the assumptions of (*a*) well-defined property rights and (*b*) zero transaction costs, the Coase theorem predicts an outcome that is both (i) efficient and (ii) invariant to the initial allocation of the property rights.[3] Efficiency is simply "secured by defining entitlements clearly and enforcing private contracts for their exchange" (Cooter 1989, 65).

The Coase theorem laid the foundation for the cap-and-trade approach in environmental economics. Following the reasoning of Coase, Dales (1968, 801) suggested that the government should "therefore issue x pollution rights and put them up for sale." In practice, the Coase theorem has inspired the American use of tradable pollution permits for sulfur dioxide, lead additives, and water discharge rights (Chichilnisky and Heal 2000, 18).

[3] Here I follow Cooter (1989, 65), Posner (1993, 195), Mas-Colell, Whinston, and Green (1995, 357), and Medema and Zerbe (2000).

Critique of Coase.—Beyond cap-and-trade, however, the influence of the Coase theorem on environmental policy has been limited. Pethig (2001, 372–73) explains that “in relevant empirical cases of environmental externalities, the qualifiers of the Coase theorem, zero ‘transaction costs’ and well-defined property rights, did not apply.” First, assuming away transaction costs is obviously unrealistic when emission rights are intangible and cannot be easily measured, monitored, and enforced. Second, international emission rights are not well specified and there is no world government that can define them.[4] Thus, pollution markets do not arise spontaneously (Cooter 1989). In addition, Coasian bargaining is dismissed because it presumably requires that every affected party be at the bargaining table. As claimed by Helfand, Berck, and Maull (2003, 259), “An obvious condition that must hold for a Coasean solution to be efficient is that there must be no effects on third parties, i.e., any parties that do not negotiate. That is, there can be no effects external to the negotiators.” This critique is important since parties often have incentives to opt out of such negotiations (Dixit and Olson 2000).[5]

Carbon leakage.—Much of the literature on international environmental economics relies on the critique of the Coase theorem. The growing literature on carbon leakage is based on the prediction that not all countries will participate in the coalition and that one cannot negotiate with nonparticipants.[6] Without a global environmental agreement, 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, Morey, and Olewiler 1993, 1995). The typical second-best remedy is to set tariffs or border taxes (Markusen 1975; Hoel 1996; Rauscher 1997; Elliott et al. 2010). However, the coalition has an incentive to set tariffs also to improve its terms of trade.[7] Most of this

[4] Well-defined property rights are necessary for the Coase theorem according to, e.g., Dales (1968, 795), Cooter (1982, 28), Posner (1993, 202), and Mas-Colell et al. (1995, 357), and they also seem to be necessary in practice (Alston and Andersson 2011). To my knowledge, only Usher (1998) finds well-defined property rights to be unnecessary for the Coase theorem.

[5] For additional critique of the Coase theorem, see Medema and Zerbe (2000).

[6] 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). Using an axiomatic approach, Maskin (2003) shows that the coalition tends to be small if its formation benefits nonparticipants. See also Ray and Vohra (2001).

[7] Certain environmentally motivated border measures are indeed permitted by the World Trade Organization, and the Montreal Protocol on Substances That Deplete the Ozone Layer, signed in 1987, does contain the possibility of restricting trade from noncompliant countries. However, Rauscher (1997, 3) observes that “green arguments can

literature focuses on demand-side climate policies. The model by Hoel (1994) is somewhat more general in that it allows the coalition to also limit its supply. However, there is carbon leakage on the supply side as well.

Current contribution.—Since the game by Hoel is a proper subgame of the game below, I generalize several of the above results before obtaining my main result. By accepting the above critique of the Coase theorem, my model requires neither a market for clean air nor negotiations over emission levels. Whether such a market is absent because of ill-defined property rights or high transaction costs is irrelevant here. My contribution is simply to emphasize the link between the emission and its source: the deposits. In contrast to emission levels, deposits are tangible, well defined, and possible to protect. So, even if a market for clean air or intangible emission rights does not exist, the physical deposits may be tradable. In an example with linear demand and supply, Bohm (1993) investigated when a reduction in consumption should be accompanied by an identical reduction in supply, perhaps necessitating the purchase or lease of foreign deposits. Bohm documented that such trade could be realistic in practice. The question is whether it ensures efficiency.

Theorem 1 provides the answer. It turns out that there exist deposit allocations implementing the first-best. This claim may be surprising since, for a generic allocation, nonparticipants consume too much, supply too much, and invest too little in green technology whereas the coalition's policy distorts trade. Given the existence of such first-best allocations, one may expect them to result from Coasian negotiations. But the "obvious condition" of Helfand et al. is not satisfied: trade in deposits is assumed to be bilateral, and proposition 1 states that third parties typically benefit or lose. Nevertheless, when all bilateral trading surplus is exploited, the equilibrium allocation is always one of those implementing the first-best.[8] In short, the solution to environmental problems does not require well-defined pollution rights, ex post negotiations, and multilateral negotiations as long as key inputs are tradable ex ante.

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." In fact, a country may benefit from being harmed by pollution if that can justify border measures (Liski and Tahvonen 2004).

[8] This result may appear to contradict the inefficiencies that arise from side contracting (Jackson and Wilkie 2005) or trade under externalities (Jehiel and Moldovanu 1995), but the intuition is that the externality on third parties is exactly zero at the equilibrium allocation (as in Segal 1999, proposition 3).

C. *Applicability and Alternative Applications*

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.[9] The main purpose of this paper is to investigate the case for an international climate policy that utilizes such a market.

The proposed policy is actually simple to implement once the market for deposits has cleared: the coalition needs only to set aside certain deposits by, for example, setting a Pigouvian extraction tax. The coalition has neither the desire nor the need to regulate consumption or trade in addition. As explained by Metcalf and Weisbach (2009), an upstream tax is simpler to administer because of the relatively few sources. Furthermore, instead of the purchase of foreign deposits, note that a leasing arrangement may suffice.

Paying for the conservation of a territory is not unrealistic. The Nature Conservancy uses land acquisition as a principal tool of its conservation effort in the United States (http://www.nature.org/aboutus/privatelandsconservation/index.htm?s_intc = subheader). Internationally, debt-for-nature swaps go back at least to 1987 when Conservation International and the Frank Weeden Foundation purchased $650,000 of Bolivia's external debt (for $100,000) in exchange for the protection of nearly 4 million acres of forest and grassland in the Beni River region (Walsh 1987). Such debt-for-nature swaps can indeed be viewed as Coasian bargaining (Hobbs 2001, 3), and the logic behind these transactions is thus analogous to the reasoning in this paper.

The most recent example is Reducing Emissions from Deforestation and Forest Degradation (REDD) funds. If the North would like to preserve tropical forests in the South, then boycotting the logged timber may be ineffective since the timber price thereby declines, 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 emergence of REDD funds is consistent with this conclusion. Such funds have now been set up by the United Nations, the World Bank, and the Norwegian government. Alston and Andersson (2011) explain that the REDD mechanism is market based and interpret it as an outcome of Coasian bargaining. In their view, the main obstacle to efficiency is that transaction costs are high and property rights often unclear. For REDD to work effectively, they claim, property rights must be sorted out. Fossil-fuel deposit markets are not likely to face the same obstacle, however, since such deposits are often nationally owned. The

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

concluding section explains how the design of REDD policies can be guided by the following analysis.

II. The Basic Model

Although the reasoning below fits alternative applications, I let anthropogenic climate change guide the modeling. There are two sets of countries: one set, M, participates in the climate treaty while the other set, N, does not. I will abstract from internal conflicts or decision making within M and treat M as one player or country. The nonparticipating countries in N interact with each other and with M only through markets.

The market for fuel.—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 quasi-linear utility functions, the objective functions are

$$U_i = B_i(y_i) - C_i(x_i) - p(y_i - x_i) \quad \text{if } i \in N,$$

$$U_i = B_i(y_i) - C_i(x_i) - p(y_i - x_i) - H\Big(\sum_{M \cup N} x_i\Big) \quad \text{if } i = M,$$

where the harm $H(\cdot)$, 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.[10] There is no regulation in nonparticipating countries, and their inhabitants choose x_i and y_i taking the fuel price as given. All these assumptions are relaxed in Section IV, which also allows various fuels (such as gas and coal) to differ in their environmental impact.

Environmental policy.—The coalition sets climate policies to reduce the environmental harm. For example, if M relies on quotas for extraction and consumption, then it sets x_M and y_M directly. 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, the outcome would be

[10] Analogously, it may be difficult to liberalize trade policies for political reasons, and being committed by a trade treaty might be necessary (Hoekman and Kostecki 2001).

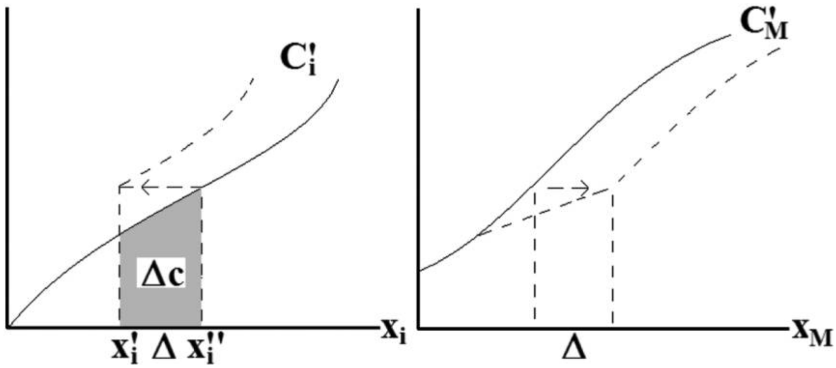

FIG. 2.—If country i sells deposits to M, both cost curves shift

identical if M could instead choose x_M and p and then 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 an equivalent export subsidy) if the tax revenues are redistributed lump-sum. Any tax vector $\tau = \{\tau_x, \tau_y, \tau_I\}$ is going to pin down x_M, y_M, and p, and the choice between quotas and taxes is therefore immaterial in this model.[11] In any case, the equilibrium fuel price is influenced by M's policies, and M does take this effect into account.

The market for deposits.—The novel part of the model is that I endogenize $C_i(\cdot)$ by allowing for trade in deposits. There is a continuum of deposits, and the cost function $C_i(\cdot)$ implicitly orders a country's deposits according to their extraction costs. This ordering 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. In other words, $C_i'(\cdot)$ is a mapping from country i's deposits, ordered according to costs, to the marginal extraction cost of these deposits. A small deposit ordered between, say, x_i' and x_i'' is characterized by its size or fossil-fuel content, $\Delta \equiv x_i'' - x_i'$, and by its marginal extraction cost, often referred to as $c \equiv [C_i(x_i'') - C_i(x_i')]/\Delta$.[12]

In the deposit market, M may purchase from $i \in N$ the right to exploit such a deposit. This trade will shift both $C_i'(\cdot)$ and $C_M'(\cdot)$ from the solid to the dotted lines in figure 2. As a result, C_i' may be a correspondence,

[11] This invariance is in line with results in Weitzman (1974), which shows that uncertainty is necessary to rank quotas and taxes.

[12] It may be helpful to further clarify the relationship between c and $C_i'(\cdot)$. While $C_i'(\cdot)$ describes i's marginal extraction cost correspondence, given a set of deposits, c represents the actual extraction cost for a specific but small (marginal) deposit. Different marginal deposits have different c's, and when ordering country i's deposits according to costs, the cost correspondence is given by $C_i'(\cdot)$, whereas $C_i'(x_i)$ is the actual marginal cost when x_i units are extracted.

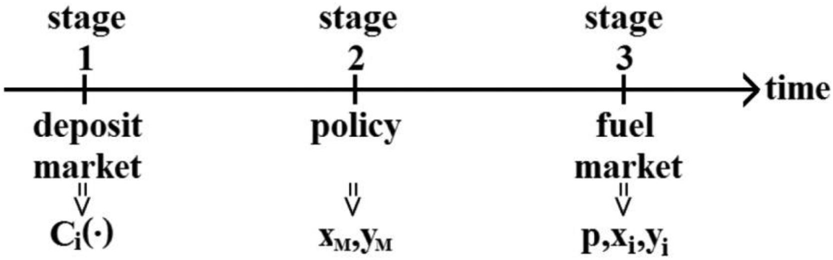

FIG. 3.—Timing of the game

and not a function, in which case we define

$$C_i'(x_i) \equiv \left[\lim_{\epsilon \uparrow 0} C_i'(x_i + \epsilon),\ \lim_{\epsilon \downarrow 0} C_i'(x_i + \epsilon)\right].$$

The market is cleared if and only if there exists no pair of countries $(i, j) \in (M \cup N)^2$ and no price of deposits such that both i and j strictly benefit from transferring the right to exploit 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 $C_i(\cdot)$ and $C_M(\cdot)$, constitutes an equilibrium. The timing of the game is given by figure 3.[13]

Price-taking behavior.—It is convenient to assume that (i) nonparticipants take the price as given at stage 3 but (ii) they anticipate that deposit trading at stage 1 may affect M's policy at stage 2 and thus the price at stage 3. Note that the two assumptions are not conflicting: if it is impossible to set taxes for political reasons (unless the country signs an international treaty), individuals are likely to take the price as given even though the government, when selling national deposits, anticipates the effect on price. Alternatively, the price may be given by M's policy set after stage 1 but before stage 3.[14] In any case, assumption i is made for simplicity and to follow the literature, and assumption ii is made to rule out unreasonable equilibria. Section IV.E discusses how these assumptions can be relaxed and argues that the results are not sensitive to these assumptions.

A general equilibrium version.—While the model is presented as a partial equilibrium model (following Hoel [1994]), a simple general equilib-

[13] While trade endogenizes each country's extraction cost function, the aggregate worldwide cost function is exogenously given. For any allocation of deposits, it can be written as

$$C(x) = \min_{\{x_i\}} \sum_{M \cup N} C_i(x_i) \quad \text{subject to} \quad \sum_{M \cup N} x_i = x.$$

[14] Instead of maximizing U_M by choosing x_M and y_M at stage 2, suppose that M chooses p and, say, x_M. The first-order conditions for the policy are going to be the same.

rium story can easily be created: Assume that a numeraire good w_i ("wheat") can be produced using a single available factor ("labor"). Country i is endowed with L_i units of labor with productivity a_i. Thus, one unit of labor produces a_i units of wheat in country i. The marginal benefit of wheat is assumed to be constant and equal to one for every country. The human capital required for extracting x_i units is measured by $C_i(x_i)$. With these assumptions, the production possibility frontier is given by $(w_i, x_i) \in (a_iL_i - C_i(x_i), x_i | x_i \geq 0)$. If i's consumption of fuel is larger than its supply ($y_i > x_i$), then wheat must be sold, in return, and p measures the price of oil relative to wheat. The welfare of country i, given its deposits, is $B_i(y_i) + a_iL_i - p(y_i - x_i) - C_i(x_i)$ minus the environmental harm. Note that this welfare is the same as before (except for the constant a_iL_i). Since the marginal utility of wheat is constant, there is no scope for exploiting market power in the wheat market. At the deposit market, a pair of countries may trade a deposit, and in return, the buyer has to give up wheat or money (used to purchase wheat). This general equilibrium story is formalized exactly as above, although one must assume a_iL_i to be so large that every country produces at least some wheat (i.e., the constraint $C_i(x_i) \leq a_iL_i$ never binds, even after deposits have been purchased). Interestingly, the environmental harm can now be interpreted as a drop in the production of wheat.

III. The Equilibrium

As a benchmark, 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:

$$\begin{gathered} B_i'(y_i^*) = B_j'(y_j^*) \quad \text{and} \\ B_i'(y_i^*) - H'\Big(\sum_{M\cup N} x_i^*\Big) \in C_i'(x_i^*) \quad \forall i, j \in M \cup N. \end{gathered} \tag{1}$$

Since these conditions uniquely pin down the efficient outcome, given an allocation of deposits, a comparison to the equilibrium will be feasible.[15]

A. *The Market for Fuel*

At the third stage, nonparticipating countries consume according to

$$B_i'(y_i) = p \Rightarrow y_i = D_i(p) \equiv B_i'^{-1}(p). \tag{2}$$

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, profit-maximizing

[15] Note that I presume, for simplicity, that the first-best solution is interior and does not require zero consumption for some countries, e.g.

extraction requires $p \in C_i'(x_i)$. Since $C_i(\cdot)$ is a strictly convex function, the correspondence $C_i'(\cdot)$ is invertible and its inverse, $x_i = S_i(p) \equiv C_i'^{-1}(p)$, is a function:

$$p \in C_i'(x_i) \Rightarrow x_i = S_i(p) \equiv C_i'^{-1}(p) \quad \forall i \in N. \tag{3}$$

Obviously, if $C_i'(x_i)$ is nonsingular at x_i, then its inverse is flat, implying $S_i'(p) = 0$ at each $p \in C_i'(x_i)$. In equilibrium, p is such that the market clears:

$$S(p) - D(p) \equiv I = y_M - x_M, \tag{4}$$

where

$$S(p) \equiv \sum_N S_i(p),$$

$$D(p) \equiv \sum_N D_i(p).$$

B. *Equilibrium Policies*

For the coalition, supply and demand depend on the policies chosen at the second stage. In particular, suppose that coalition M chooses x_M and y_M to maximize its payoff:

$$U_M = B_M(y_M) - C_M(x_M) - H\left(x_M + \sum_N x_i\right) - p(y_M - x_M), \tag{5}$$

taking into account the outcome at stage 3, as given by (2)–(4). These constraints show that the nonparticipants' demand and supply depend on the market price. This price will be influenced by M's policy, thanks to the market-clearing condition (4). The outcome is as in Hoel (1994).

LEMMA 1 (Hoel 1994). Coalition M's equilibrium policy implements

$$\left[\frac{S'(p)}{S'(p) - D'(p)}\right]H' + \frac{y_M - x_M}{S'(p) - D'(p)} = B_M'(y_M) - p, \tag{6}$$

$$\left[1 - \frac{S'(p)}{S'(p) - D'(p)}\right]H' - \frac{y_M - x_M}{S'(p) - D'(p)} \in p - C_M'(x_M). \tag{7}$$

Proof. To see the impact of a marginal change in M's policy, measured by dy_M and dx_M, differentiate (2)–(4) to get

$$dy_i = D_i'(p)dp \quad \forall i \in N, \tag{8}$$

$$dx_i = S_i'(p)dp \quad \forall i \in N, \tag{9}$$

$$dy_M - dx_M = \sum_N (dx_i - dy_i).$$

By inserting (8) and (9) into the third equation, we can see how p varies with dy_M and dx_M:

$$\frac{dp}{dy_M - dx_M} = \frac{1}{S'(p) - D'(p)}.$$

Substituted into (8) and (9), we learn how nonparticipants react to M's policy:

$$\frac{dy_i}{dy_M - dx_M} = \frac{D_i'(p)}{S'(p) - D'(p)} \quad \forall i \in N,$$

$$\frac{dx_i}{dy_M - dx_M} = \frac{S_i'(p)}{S'(p) - D'(p)} \quad \forall i \in N.$$

The first-order conditions when (5) is maximized with respect to y_M and x_M become (6) and (7), respectively. The second-order conditions hold if $C_M(\cdot)$ and $H(\cdot)$ are sufficiently convex, and it can be shown that they always hold when the deposit market clears. QED

Marginal costs and benefits equal p for every nonparticipant, but not for the coalition when the left-hand sides of (6) and (7) are different from zero. To understand the effects of the two terms, isolate the first by assuming $y_M \approx x_M$. The left-hand sides are then always positive when $H' > 0$, which implies that M is consuming less than the level that would have equalized its marginal benefit to the price, and M extracts less than the level that would have equalized its marginal extraction cost to the price. With such a policy, M reduces global emissions.

However, when M reduces its consumption, p decreases and N consumes more. This demand-side leakage is particularly large if $|D'(p)|$ is large. The coalition would then hesitate to reduce its consumption, preferring instead to rely on supply-side policies. If M reduces its supply, however, p increases, N extracts more, and the magnitude of this supply-side leakage is increasing in $S'(p)$. Lemma 1 shows that M prefers to focus on reducing its supply rather than its demand if and only if $S'(p)$ is small relative to $|D'(p)|$.

The second terms of (6) and (7) remain even if $H' \approx 0$, and they show how the policy should be in order to improve M's terms of trade. If M is a net importer of fuel, it prefers to reduce its consumption and increase its supply, since both policies reduce the price for fuel. If M is a net exporter, it prefers to increase consumption and reduce supply in order to raise the price.

Taxes on emission and extraction.—The outcome is identical to that above if M sets taxes at stage 2 and lets the market clear at stage 3. With the consumption tax τ_y and the production or extraction tax τ_x, M's consumers and producers ensure that, at stage 3,

$$B'_M(y_M) = p + \tau_y \quad \text{and} \quad p - \tau_x \in C'_M(x_M).$$

As noted by Hoel (1994), M's optimal policy (6)–(7) is implemented by

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

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

Note that the sum of the taxes is always equal to H', the marginal harm. If $H' = 0$, we have

$$\frac{\tau_y}{p} = -\frac{\tau_x}{p} = \frac{(y_M - x_M)/p}{S'(p) - D'(p)} = \frac{I}{p}\frac{\partial p}{\partial I} \equiv \frac{1}{\eta_N},$$

where $I \equiv y_M - x_M$ is both M's net import and N's net export, and η_N measures the elasticity of N's export. If M is importing fossil fuel, M prefers to tax consumption but subsidize extraction, since both policies lower the world price of fuel and thus M's import expenditures. If M exports fossil fuel, M prefers to tax extraction but subsidize consumption in order to raise the fuel price. The equilibrium tax/subsidy decreases in N's export elasticity.

Tariffs and trade policies.—Policy (6)–(7) can also 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):

$$\tau_I = B'_M(y_M) - p = \left[\frac{S'(p)}{S'(p) - D'(p)}\right]H' + \frac{y_M - x_M}{S'(p) - D'(p)}, \tag{10}$$

$$\tau_x = B'_M(y_M) - C'_M(x_M) = H'. \tag{11}$$

The optimal production tax is Pigouvian, and, given p, the emission from M's supply is thus independent of the terms-of-trade effects. This finding 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. If M is exporting, the optimal export subsidy is τ_I, or if negative, then M sets an export tax equal to $-\tau_I$. The more M exports, the larger its export tax.[16]

C. *When Are There Gains from Trade in Deposits?*

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

PROPOSITION 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

$$\max\{0,\ c + H' - B_M'(y_M)\} + (x_i - y_i)\frac{\partial p}{\partial \Delta} > 0; \tag{12}$$

(b) $\sum_{M\cup N} U_i$ increases if and only if

$$\max\{0,\ c + H' - B_M'(y_M)\} + \sum_N (x_i - y_i)\frac{\partial p}{\partial \Delta} > 0, \tag{13}$$

where $\partial p/\partial \Delta > 0$.

Part a describes when i and M can benefit if i sells a deposit to M. If (12) 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 part a, suppose that the last term in (12) is negligible (e.g., 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 a deposit to M, country i exports less and M imports less. By lemma 1, M finds it optimal to rely less on demand-side and more on supply-side policies, and the equilibrium fuel price is slightly increased. Thus, $\partial p/\partial \Delta > 0$. Coalition 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

[16] With all three tax instruments, M's consumers and producers ensure that, at stage 3,

$$B_M'(y_M) = p + \tau_y + \tau_I,$$

$$C_M'(x_M) = p - \tau_x + \tau_I.$$

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

to sell a deposit even if it has a high extraction cost and M would have preserved rather than exploited it. In sum, it is more likely that i sells a 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 the gains from trade.

Part b states when such a trade is beneficial for the society as a whole. Condition (13) is different from (12), thanks to the effect on p. If $i \in N$ sells a deposit to M, p increases. The price increase is beneficial to every exporter but harmful to every importer. If the other countries are, on average, fuel importers, then i and M may trade a deposit even though this will reduce welfare for the world as a whole. If the other countries are, as a group, exporters, then i may not sell a deposit to M even though such a trade would be beneficial for the world.

D. *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. Let Ω^{eq} denote the set of equilibrium deposit allocations and Ω^* the set of allocations such that M's equilibrium policy (6)–(7) implements the first-best (1). Both these sets are nonempty, it turns out, and they are closely related.

THEOREM 1. In every equilibrium of the deposit market, M's equilibrium policy (6)–(7) implements the first-best: $\Omega^{eq} \subset \Omega^*$.

The theorem may surprise since, for a generic allocation of deposits, stages 2 and 3 are inefficient thanks to free-riding, consumption leakage, production leakage, and M's market power. In addition, proposition 1 states that, at stage 1, i and M may trade a deposit too often or too seldom. It turns out that all these problems vanish for some particular allocations of the deposits, Ω^*. More important, all equilibrium allocations Ω^{eq} are among these first-best allocations.

The theorem follows from lemmas 2 and 3, proved in the Appendix.

LEMMA 2. In every equilibrium, $x_i = y_i$ for all $i \in M \cup N$.

When the market for deposits clears, every country expects to rely on neither imports nor exports of fossil fuel. That this equilibrium is feasible should not be surprising since M can equally well sell a deposit to i as sell the fuel exploited afterward. Lemma 2 goes further, however, in claiming that $x_i = y_i$ always. This equality follows from proposition 1: Suppose that $i \in N$ is an exporter of fuel. If M buys a small deposit from i, which is such that any owner would exploit it ($c < B'_M - H'$), then M imports less afterward. As a consequence, p increases and the exporting country benefits. Thus, i requires less when selling the deposit than M is willing to pay. In equilibrium, therefore, i cannot be an exporter. For analogous reasons, i cannot be an importer either.

The next stepping-stone for the theorem is lemma 3.

LEMMA 3. In every equilibrium, $S_i'(p) = 0$ for all $i \in N$.

In other words, $C_i'(\cdot)$ is vertical and jumps at the equilibrium x_i, $i \in N$. As suggested by proposition 1, the reason is that M is willing to purchase the deposits that $i \in N$ 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 $c \approx p$. Hence, when the market for deposits clears, the supply of $i \in N$ is locally inelastic.

Combined, lemmas 1–3 imply that the outcome is first-best: 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 policies. 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.

In retrospect, it is simple to show that $\Omega^{\text{eq}} \neq \emptyset$. To construct an equilibrium deposit allocation, note that the first-best defines a set of deposits that ought to be extracted, and it requires that the consumed fuel is distributed such that $B_j'(y_j) = B_i'(y_i)$ for all $i, j \in M \cup N$. Now, allocate the deposits that ought to be extracted (arbitrarily) such that the extracted amount for i is $x_i = y_i$, and let M own the remaining deposits. Given that $\Omega^{\text{eq}} \neq \emptyset$ and $\Omega^{\text{eq}} \subset \Omega^*$, it follows that $\Omega^* \neq \emptyset$.

The lemmas are stronger than what is necessary for efficiency, and Ω^{eq} is a proper subset of Ω^*. In equilibrium, $x_i = y_i$ for every country. However, when $S'(p) = 0$ and every deposit satisfying $c \in (p - H', p)$ is owned by M, then (6) and (7) implement the first-best if simply $x_M = y_M$. In other words, it is not necessary for efficiency that every nonparticipant imports zero, as long as the coalition is a nontrader and, hence, is disinterested in influencing the world price. In fact, also, $x_M = y_M$ is stronger than what is necessary for efficiency.[17]

[17] For example, if M had already agreed on a certain level of market access (I) at some price, then its second-period policy would never be aimed at affecting its terms of trade. In this situation, the first-best is implemented if M purchases and conserves only the marginal deposits (I am grateful to Bob Staiger for this suggestion).

IV. Generalizations

The next four subsections strengthen the theorem by allowing for investments in green technology, multiple periods, heterogeneous fuel, and nonparticipants that are harmed by the emissions. The final two subsections discuss alternative market structures and the incentive to participate in the coalition. Each extension builds on the basic model and can be read on its own.

A. Endogenous Technology

Technology may help to reduce emissions. An important extension of the above model is thus to endogenize the technologies and let countries invest in them. This possibility, 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 $k_i'(\cdot)$, $k_i''(\cdot) > 0$. To simplify, there are no spillovers or trade in technologies. The new technology is a substitute for consuming fossil fuels, and it can represent, for example, the stock of windmills or renewable energy sources. Thus, country i consumes energy from two sources, and we may write its total benefit as $\tilde{B}_i(y_i + r_i)$. The term *preinvestment policy* will refer to the case in which investments take place between stage 2 and stage 3. The term *postinvestment policy* will refer to the situation in which they take place between stage 1 and stage 2. Solving the game by backward induction, I start with an arbitrary allocation of deposits before describing the deposit market equilibrium.

Equilibrium investment levels.—Let $i \in M \cup N$ be a price taker when investing, for example, because investments are made by private entities in country i. Then $\tilde{B}_i'(\cdot)$ is the marginal willingness to pay for new technology in country i, and the equilibrium investment level must satisfy

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

Is M's investment level r_M optimal? From M's point of view, it is, indeed. 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 $\tilde{B}_M'(\cdot)$. However, the reduced 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 2. The coalition's equilibrium investment level is smaller than the first-best level if $x_M > y_M$ and larger than the first-best level if $x_M < y_M$.

Are the nonparticipants' investments optimal? A larger r_i reduces i's need to buy fossil fuel, and the fuel price declines. This decline is good for an importer, but from a social point of view, all the terms-of-trade effects cancel.[18] However, the lower fuel price reduces supply when supply is somewhat elastic (i.e., when $S' > 0$), and emissions will then decline. This benefit to M is not internalized by the foreign investors, and they will thus invest too little compared to the social optimum when $S' > 0$, no matter how the investments are timed.

PROPOSITION 3. (*a*) The investment levels in nonparticipating countries are lower than the socially optimal level and strictly lower if and only if $S'(p) > 0$. (*b*) The benefit for M of i's marginal investment is given by

$$\frac{\partial U_M}{\partial r_i} = \left\{\frac{S'(p)}{\sum_N [S_i'(p) - 1/B_i''(p)]}\right\}H' + \frac{y_M - x_M}{\sum_N [S_i'(p) - 1/B_i''(p)]} \quad \forall i \in N. \tag{14}$$

The first term on the right-hand side of (14) 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 (14) 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 nonparticipants to invest more.

The coalition's equilibrium policy at stage 2.—Suppose, first, that the investments have taken place when M sets its policy. Then, as before, M's policy is given by lemma 1 and $D_i' = 1/B_i''$. Substituting $D_i' = 1/B_i''$ into (14) and combining with (6), we get

$$\frac{\partial U_M}{\partial r_i} = \tilde{B}_i(y_i + r_i) - p,$$

which is equal to M's ideal consumption tax, or tariff. When this ideal 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 M's policy is set before the investment stage, then M can indeed influence i's investment: a larger p will not only reduce i's consumption but also increase i's investment. To raise p and encourage more investments, M's supply should be lower, whereas its consumption should be larger relative to the levels that M would choose after the investment stage. Formally, we have the following proposition.

[18] 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 $\partial U_i/\partial r_i = \tilde{B}_i'(\cdot) - (y_i - x_i)\partial p/\partial r_i$, $\partial U_j/\partial r_i = -(y_j - x_j)\partial p/\partial r_i$, and $\partial U_M/\partial r_i = -(y_i - x_i)\partial p/\partial r_i - H'(\cdot)\partial(\sum_N x_i)/\partial r_i$. When we sum over these, the terms-of-trade effects cancel since $\sum_{M\cup N}(y_i - x_i) = 0$.

Proposition 4. The equilibrium policy is given by lemma 1 whether the policy is chosen before or after the investments. However, the demand is more elastic when the policy is chosen first:

$$D_i'(p) = \frac{1}{\tilde{B}_i''(y_i + r_i)} - \frac{1}{k_i''(r_i)} < 0$$

for preinvestment policies and

$$D_i'(p) = \frac{1}{\tilde{B}_i''(y_i + r_i)} < 0$$

for postinvestment policies.

If M sets policies before the investment stage, foreign demand is more elastic: a large $p = \tilde{B}_i'(y_i + r_i)$ then both reduces $y_i + r_i$ and increases r_i, given by $k_i'(r_i) = p$, and the larger r_i requires a further decline in y_i to satisfy $p = \tilde{B}_i'(y_i + r_i)$. If the last two terms in (6) are positive, they decrease in $|D_i'(p)|$, ceteris paribus. As a consequence, x_M must decline (or the extraction tax must increase) but y_M must increase (or the consumption tax must decline) if M's policy is chosen before rather than after the investment stage. After the investments are sunk, however, M would like to revise this policy since $|D_i'(p)|$ is then smaller.

To sum up so far, for a generic distribution of deposits, investments in renewable energy are suboptimal for all countries. Nonparticipants invest too little, reinforcing their tendency to emit too much. To encourage them to invest more, M would like to commit to a policy focusing on the supply (by reducing x_M) rather than the demand (requiring a smaller y_M). But without the possibility of committing, this policy may not be time consistent.

The deposit market at stage 1.—With the additional inefficiencies, the gains from trade in deposits are actually larger than in Section III. 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. The theorem continues to hold.

Theorem 1(ii). Let countries invest before or after the policy stage. In every equilibrium of the deposit market, the outcome is first-best: $\Omega^{eq} \subset \Omega^*$.

The result follows, almost as a corollary, from propositions 2–4 and lemmas 1–3. If the equilibrium in the deposit market is as described in Section III, then $y_i = x_i$ and M's investment is optimal, according to proposition 2. Lemma 3 states that $S_i'(p) = 0$ for all $i \in N$, and proposition 3 then implies that all countries invest optimally. Since the equilibrium policy, given by lemma 1, does not depend on $D_i'(\cdot)$ when $\sum_N S_i' = 0$, M's policy is the same whether it is set before or after investments, despite proposition 4. Finally, when lemmas 2 and 3 are combined with proposition 3, $\partial U_M/\partial r_i = 0$. In other words, M has no interest in influencing r_i, and the deposit allocation described by lemmas 1–3 continues to be an equilibrium. The proof that the lemmas must hold in all equilibria follows the same steps as before.

B. Multiple Periods and the Green Paradox

The problems of climate change and how to optimally exploit exhaustible resources are both dynamic in nature. It is thus reassuring that the theorem does not necessarily change in a dynamic model.

Suppose that each marginal deposit has a fixed extraction cost but can be extracted only once. Assume, further, that the environmental damage $H(\cdot)$ 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 needs to buy and set aside certain deposits only 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, there will be intertemporal leakages in addition to the inefficiencies already discussed. If M is expected to reduce its future consumption, the expected future price declines and it becomes 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 pollution (today). Clearly, the green paradox reduces the value of an anticipated demand-side policy.[19]

A model.—To illustrate, suppose that 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 $C_i(\cdot)$ is i's extraction cost function, the cost of extracting $x_{i,1}$ units in period 1 is $C_i(x_{i,1})$, and the remaining cost of extracting the additional $x_{i,2}$ in period 2 is $C_i(x_{i,1} + x_{i,2})$ minus the cost already paid, $C_i(x_{i,1})$. To capture the intuition that climate change is a long-term problem, let the harm $H(\cdot)$ be experienced only in the second period. When the prices in periods 1 and 2 are p_1 and p_2, the payoff for $i \in M \cup N$ is

$$\begin{aligned} U_i = {} & B_{i,1}(y_{i,1}) - C_i(x_{i,1}) + p_1(x_{i,1} - y_{i,1}) \\ & + \delta[B_{i,2}(y_{i,2}) - C_i(x_{i,1} + x_{i,2}) + C_i(x_{i,1}) + p_2(x_{i,2} - y_{i,2})] \\ & - \delta H\Big(\sum_{t\in\{1,2\}} \sum_{j\in M\cup N} x_{j,t}\Big)\Upsilon_i, \end{aligned} \tag{15}$$

[19] 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.

where the index function $\Upsilon_i = 0$ for $i \in N$ and $\Upsilon_M = 1$. Solving the game by backward induction, we start with an arbitrary allocation of deposits.

Equilibrium policy with and without commitment.—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 a marginal deposit now or later. The outcome is $x_{i,1} = S_i((p_1 - \delta p_2)/(1-\delta))$.[20] In each period, the market must clear such that

$$I_t \equiv y_{M,t} - x_{M,t} = \sum_N (x_{i,t} - y_{i,t}) \quad \forall t \in \{1, 2\}.$$

The coalition's optimal policies for both periods are derived in the Appendix.

PROPOSITION 5. If M can commit, its second-period policies are given by

$$\left[\frac{dp_2}{dI_2} S'(p_2)\right] H' + \frac{dp_1}{dI_2}\frac{I_1}{\delta} + \frac{dp_2}{dI_2} I_2 = B_{M,2}'(y_{M,2}) - p_2, \tag{16}$$

$$\left[1 - \frac{dp_2}{dI_2} S'(p_2)\right] H' - \frac{dp_1}{dI_2}\frac{I_1}{\delta} - \frac{dp_2}{dI_2} I_2 \in p_2 - C_M'(x_{M,1} + x_{M,2}), \tag{17}$$

where

$$\frac{dp_2}{dI_2} = \frac{S_1' - (1-\delta)D_1'}{[S'(p_2) - D_2'][S_1' - (1-\delta)D_1'] - \delta S_1' D_1'},$$

$$\frac{dp_1}{dI_2} = \frac{\delta S_1'}{[S'(p_2) - D_2'][S_1' - (1-\delta)D_1'] - \delta S_1' D_1'},$$

$$S_1' \equiv S'\left(\frac{p_1 - \delta p_2}{1-\delta}\right).$$

If M cannot commit to future policies, its second-period policy is given by lemma 1 above. In both cases, the sum of the taxes must equal the marginal environmental harm. However, the two policies are, in general, quite different. On the one hand, in the first period M would like to set second-period policies considering the effect on its terms of trade not only for the second period but also for the first. Once the second

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

period has arrived, this effect is sunk, and M would like to revise its policy to satisfy lemma 1. If M cannot commit, its ideal policy is not time consistent, even in the absence of environmental harm.[21]

On the other hand, if we also abstract from the terms-of-trade effects by assuming $I_1 = I_2 = 0$, M's preferred policy under commitment is generally different from the equilibrium policy when it cannot commit. In particular, note that $dp_2/dI_2 < S'(p_2) - D_2'$, so the optimal consumption tax, given by the left-hand side of (16), is smaller than the optimal tax when the second period arrives, as given by (6). Similarly, the optimal extraction tax, given by (17), is larger than the extraction tax when M cannot commit, as given by (7). Intuitively, M would like to commit to a large fuel price in the future to discourage the nonparticipants from extracting today. This way, M would minimize the intertemporal consumption leakage and the problems of the green paradox, mentioned above. If the coalition can revise its decision, however, this policy is not time consistent.

The deposit market.—Consider now a deposit market at the beginning of period 1. For the same reason as before, lemma 2 continues to hold and $x_{M,t} = y_{M,t}$ for all $t \in \{1, 2\}$. In equilibrium, the coalition purchases the deposits that are most costly to extract. Thus, lemma 3 continues to hold for the second period (i.e., for $p = p_2$) and i's supply is then inelastic. When we substitute $I_1 = I_2 = 0$ and $S_i'(p_2) = 0$ in (16) and (17), it is clear that M relies entirely on supply-side policies in period 2 whether or not it can commit. Thus M's policy is 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 1(iii). Whether or not M can commit to future policies, in every equilibrium of the deposit market, the outcome is first-best: $\Omega^{\mathrm{eq}} \subset \Omega^*$.

Coalition 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:[22]

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

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

[22] 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. The result would be the green paradox, discussed above, and the outcome would be dynamically inefficient. To avoid this inefficiency, the present-discounted value of the tax should be the same across periods.

This reasoning continues to hold if there are more than two periods: a deposit market at the beginning of the game will still implement the first-best.[23]

C. Heterogeneous Fuels

So far, the analysis has 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 the integral over every $e \cdot \Delta$, defined as $E_i(x_i)$. So $E_i'(x_i)$ is the marginal emission content of a deposit located at x_i. If $E_i'(x_i)$ happened to be monotonically increasing in x_i, the fuel that is most costly to extract would also be most polluting. I assume that $E_i'(\cdot)$ is continuous at x_i if $C_i'(\cdot)$ is continuous at x_i[25] and that $E_i'(x_i) \geq \bar{e}$ for all i and x_i, for some $\bar{e} > 0$. If $i \in M \cup N$ supplies x_i units, the total emission level is $\sum_{M \cup N} E_i(x_i)$, and the harm experienced by M is $H(\sum_{M \cup N} E_i(x_i))$.

At the first-best, marginal benefits are equalized across countries and a marginal deposit is extracted if and only if

$$c + eH'\Big(\sum_{i \in M \cup N} x_i\Big) \leq B_j'(y_j) = B_i'(y_i) \quad \forall i,\, j \in M \cup N. \tag{18}$$

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

LEMMA 4. Coalition M's equilibrium policy implements

$$\frac{\sum_N E_i'(x_i) S_i'(p)}{S'(p) - D'(p)} H' + \frac{y_M - x_M}{S'(p) - D'(p)} = B_M'(y_M) - p, \tag{19}$$

[23] However, the coalition may have an incentive to postpone the purchase of deposits, and this can lead to inefficiency (Harstad 2012*b*).

[24] In contrast, M always exploits the deposits with the smallest $c + eH'$, so M's deposits should be ordered according to $c + eH'$, where H' is evaluated at the equilibrium pollution level.

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

$$\left[E'_M(x_M) - \frac{\sum_N E'_i(x_i)S'_i(p)}{S'(p) - D'(p)}\right]H' - \frac{y_M - x_M}{S'(p) - D'(p)} \in p - C'_M(x_M). \tag{20}$$

The lemma is a generalization of the result by Golombek, Hagem, and Hoel (1995), who extend the model by Hoel (1994) to allow for three types of fuel.

As before, the policy can be implemented by taxes on consumption and extraction equal to the left-hand sides of (19) and (20). 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. In fact, M may find it optimal to subsidize domestic extraction ($\tau_x < 0$) if E'_M is much smaller than E'_i, which would be the case if, for example, the coalition possesses natural gas whereas the nonparticipants rely on coal.

Although lemma 4 describes M's best policy for coping with free-riding and leakages, the outcome is far from efficient 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 a higher emission content and larger social cost than some other deposits that it finds too costly to exploit.

Suppose that i considers selling a marginal deposit to M. Both can benefit if condition (12) in proposition 1 is replaced by

$$\max\{0,\ c + eH' - B'_M(y_M)\} + (x_i - y_i)\frac{\partial p}{\partial \Delta} > 0. \tag{21}$$

When the deposit market clears, the outcome is familiar.

THEOREM 1(iv). Let fossil fuels vary in their emission content. In every equilibrium of the deposit market, the outcome is first-best: $\Omega^{\mathrm{eq}} \subset \Omega^*$.

Just as before, lemmas 2 and 3 continue to hold: In equilibrium, deposits are sold to importers and afterward there is no trade in fuel. Because every marginal deposit is polluting at least $\bar{e} > 0$, M purchases every marginal deposit from $i \in N$, which ends up with a locally inelastic supply curve. When $S'_i(p) = 0$ is substituted in (19), marginal benefits are equalized across countries. Every deposit satisfying $c \in (B'_M - eH', p)$ is purchased (in line with [21]) and preserved (according to lemma 4) by M. The outcome is then first-best (18).

Other usages of fossil fuel.—Just as different fuels may have different carbon content, different usages of fuel may generate different levels of emission. In particular, if the fuel is not burned but instead transformed into another material, then its usage may be less harmful. Suppose for a moment that oil can alternatively be used to produce "plastic," which I will assume is not emitting CO_2. If the demand for plastic is completely inelastic, every result above continues to hold: a certain amount of oil is always used to satisfy the demand for plastic, no matter what the oil price is, and price changes affect only the demand for energy, as above. At the other extreme, suppose that the demand for plastic is completely elastic. In this case too, the first-best is implemented in equilibrium, and it implies that only M produces and supplies the world with plastic. However, if the demand for plastic is imperfectly elastic, M would exploit its market power and reduce its supply. The first-best would then not be implemented unless the countries negotiated a trade agreement pinning down each country's tariff or level of plastic imports.

D. Shared Harm and Shared Ownership

So far, I have assumed that nonparticipants do not experience any harm from the emissions. 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 $H(\cdot)$ measures the total harm, as before, let $H_i(\cdot)$ measure the harm experienced by country i. Thus, $H(\cdot) \equiv \sum_{M\cup N} H_i(\cdot)$. The optimal x_i^*'s can be derived as before. Then, define

$$\alpha_i \equiv \frac{H_i'(\sum x_i^*)}{H'(\sum x_i^*)}.$$

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. Suppose now that ownership of fossil-fuel deposits can be similarly 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 1(v). With shared harm and ownership, there exist equilibria in the deposit market implementing the first-best: $\Omega^{eq} \cap \Omega^* \neq \emptyset$. In these equilibria, i owns α_i of every deposit satisfying

$$c \in \left(\rho - H'\left(\sum_N x_i^*\right), \rho\right), \quad \rho \equiv B_i'(y_i^*) \quad \forall i \in M \cup N. \tag{22}$$

To understand the theorem, take a small deposit of size Δ with marginal extraction cost c satisfying (22). If it were 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. That would be socially optimal since a deposit should be exploited only 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 (22), the first-best is implemented, no matter whether the owners make decisions by unanimity or by majority rule. Lemma 2 continues to hold, and after deposits satisfying (22) are set aside, further regulation is neither necessary nor desired. It follows that $B_i'(y_i^*)$ is equalized across countries.[26]

The shares α_i constitute an equilibrium since no two owners could benefit by trading such a deposit share. If the consequence following such a transaction would be that the 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 equilibrium is not unique when $|N| > 2$, 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 of preserving it. If the multiple potential owners cannot coordinate such a takeover, other equilibria exist that fail to implement the first-best.

E. The Market Structure for Fuel

So far, the analysis has rested on two assumptions: (i) every nonparticipant anticipates that trading deposits at stage 1 alters M's equilibrium policy and thus the fuel price at stage 3, but (ii) at stages 2 and 3, nonparticipants act as if they take the fuel price as given. These assumptions are not inconsistent, as already discussed. This subsection explains that assumption i is made to get rid of additional unreasonable equilibria and assumption ii is made for simplicity.

Relaxing assumption ii.—Suppose now that every country sets stage 2 policies influencing the stage 3 price. In contrast to the case analyzed above, it now matters a great deal whether the countries commit to quantities or taxes. If every country can set tariffs and production taxes at stage 2, then it is easy to show that M's policy is just as described by (10) and (11), and[27]

$$\tau_{x,i} = 0 \quad \text{and} \quad \tau_{I,i} = \frac{y_i - x_i}{\sum_{M \cup N \setminus i} (S_j' - D_j')} \quad \forall i \in N. \tag{23}$$

[26] Effectively, the appropriate division of ownership implements Lindahl prices when the public good of reduced pollution is paid for (Lindahl 1958).

[27] If every $i \in N \cup M$ were harmed by the emission, the taxes would instead be

$$\tau_{x,i} = H_i' \quad \text{and} \quad \tau_{I,i} = \frac{y_i - x_i + H_i' \sum_{M \cup N \setminus i} S_j'}{\sum_{M \cup N \setminus i} (S_j' - D_j')} \quad \forall i \in M \cup N.$$

These equations are illustrative. First, importers prefer to impose a positive tariff, improving their terms of trade, whereas exporters prefer the opposite. Nevertheless, the analysis above (assuming $\tau_{I,i} = 0$) turns out to be approximately correct if each nonparticipant is importing/exporting little or faces a world market with either a very elastic demand or a very elastic supply. Second, (23) suggests that the first-best is still possible under some allocations of deposits: if M owns all the deposits that ought to be conserved whereas every country owns deposits from which it can extract $x_i = y_i$, the first-best is implemented, just as before, since no country would like to have a tariff. Finally, if an exporter sells to an importer at stage 1, the exporter can export less and the importer can import less. As suggested by (23), the exporter will then reduce its export tax, lowering the world price, which is beneficial for the importer. Likewise, when the importer imports less, its optimal tariff declines, according to (23); the world price is then increasing and the exporter benefits. These effects suggest that both parties benefit from trading (at some price) unless $y_i = x_i$ for every i.[28] Once $y_i = x_i$, the first-best is implemented after M buys the marginal deposits from $i \in N$, just as before.

Relaxing assumption i.—At the other extreme, nonparticipants are price takers at every stage in the game. Then, nonparticipants have no incentive to set taxes at stage 2, and stage 2 as well as stage 3 is exactly as analyzed in Section III. The equilibria of the deposit market implementing the first-best continue to exist. The only difference is that other equilibria also exist.[29] These equilibria cease to exist as soon as $i \in N$ realizes that trading deposits may change the world price of fuel, at least marginally.

As a final case, suppose that every $i \in M \cup N$ takes the price as given at stages 2 and 3 (and, perhaps, even at stage 1). Then, M believes that it cannot alter consumption or production abroad, and it cannot affect its terms of trade. Since M can affect only its own emissions, its policy ensures that $B'_M = C'_M + H'$. At the same time, M benefits from purchasing and conserving every marginal deposit from $i \in N$. The outcome is then first-best without the large amount of deposit trading that might be necessary to achieve $x_M = y_M$.

[28] However, when also $j \in N \backslash i$ can set taxes at stage 2, these taxes may change after i and M trade a deposit. Calculating the total changes in utilities for i and M is thus complicated and must be left for future research.

[29] The reason is that $i \in N$ does not take into account that trading deposits with M changes the climate policy of M and, thus, the price at stage 3. The cost of giving up a deposit for $i \in N$ is therefore p, and the benefit to M is also p, so trade may or may not take place. This indeterminacy generates multiple equilibria, including some in which $y_M \neq x_M$, and these fail to implement the first-best.

F. *Participation and Political Resistance*

There is no consensus on how to endogenize participation in the most reasonable way. A common method is to introduce a stage 0 into the game, at which every player first decides whether to participate (see Dixit and Olson [2000] or the survey by Barrett [2005]). Although it is not straightforward to derive equilibria in this framework, the working paper version (Harstad 2010) derives all pure strategies equilibria, assuming that countries are symmetric whereas marginal costs and benefit functions are linear (as in Sec. I.A). The results are briefly reviewed here.

Participation without deposit markets.—If a country decides to participate, its benefit is that every existing coalition member further reduces its emission by a small amount. The new member, however, is expected to drastically cut consumption (from x' to x^* in fig. 1). This expense generates a lot of free-riding, and as in Barrett (2005), the equilibrium number of participants is just three!

Participation with deposit markets.—The participating members are always better off with a deposit market (after all, the first-best can be achieved). However, nonparticipants are also better off compared to the situation without a deposit market since the coalition is paying nonparticipants to extract less. Whether participation is more or less attractive with a deposit market depends on the structure of the deposit market. If M makes a tender (take-it-or-leave-it) offer to symmetric countries, it must pay each nonparticipating country the area $\alpha + \beta$ in figure 1. This price is so high that the motivation to participate declines compared to the situation without a deposit market, and the equilibrium number of participants is only two! On the other hand, if M needs to compensate only the producers of fossil fuel, then paying the area α suffices. Since this price is lower, participation becomes more attractive, and full participation is possible if demand is inelastic relative to supply.[30]

Political economy.—A realistic analysis of participation should also include domestic political economy forces. A tough climate policy might be supported by citizens and environmentalists, but producers as well as consumers are harmed when taxes are introduced on demand and supply. Deposit owners are geographically stuck, however, in being un-

[30] If ownership is initially concentrated, M may need to pay only $\alpha - \gamma$ if it has all the bargaining power. 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, M is going to modify its policies in a way that increases the fuel price. Thus, purchasing inputs might be substantially cheaper than Coasian bargaining to reduce nonparticipants' emission. On the other hand, if a nonparticipant makes the take-it-or-leave-it offer, M must pay $2(\alpha + \beta)$ if H is linear. The nonparticipants are then extracting the entire surplus from the deposit market, and the incentive to participate in the coalition declines. The working paper discusses alternative deposit market structures in more detail.

able to move from one country to another. Their political clout is therefore low. In contrast, industries relying on energy may credibly threaten to relocate abroad. Babiker (2005) shows that leakage can be much larger if such firms can exit and enter the market.

Without a deposit market, firms consuming fossil fuel can benefit a lot when moving from a participating country since the fuel price is likely to be much lower in nonparticipating countries. With a deposit market, however, the price is equalized across participants and nonparticipants. Consumers then have no incentive to move, which reduces their political clout when lobbying against a climate treaty. Furthermore, the incentive to lobby against participation in a climate treaty is much smaller when there is a deposit market since the consumer price is then not dramatically larger if the country decides to join the coalition.[31] For these reasons, participation in a climate treaty is likely to meet less domestic resistance if a deposit market exists.

V. Conclusions and Limitations

The analysis above suggests that the best climate policy is to purchase fossil-fuel deposits and preserve them. A climate coalition faces several dilemmas if the allocation of deposits is arbitrary: The nonparticipants extract too much, consume too much, and invest too little in green technology. If the coalition reduces its own consumption of fossil fuel, the world price declines and nonparticipants consume more. If the coalition reduces its supply, nonparticipants find it optimal to extract more. In response, the coalition's best policy distorts trade and is not time consistent.

Proposition 1 states that the coalition often benefits from purchasing and preserving a deposit that is, in any case, costly to exploit. On the one hand, the transaction may harm third parties since the prices may change. On the other, the transaction makes the foreign supply less elastic and it becomes optimal for the coalition to shift to supply-side policies rather than demand-side policies. Once the deposit market clears, the coalition implements its ideal policy simply by reducing its own extraction, without the need to also regulate consumption or trade. The outcome is then first-best, even if some countries do not participate in the coalition.

More generally, the results show that efficiency can be obtained without Coasian bargaining ex post if crucial input factors are tradable ex

[31] The price may increase somewhat, of course, since a larger number of participants increases the coalition's total harm, making it optimal to further reduce total emission. However, the change in price is even larger for a country that is considering whether to join the coalition if there is no deposit market (since the price is then higher inside than outside the coalition, unless the coalition is a major exporter).

ante. This insight can be applied to other environmental problems as well. For example, suppose that the North would like to preserve tropical forests. A boycott of the logged timber would decrease the world price and lead other countries to raise their import of the timber. To prevent such leakage, a wiser strategy may be to purchase the forests or pay countries to preserve them. The recent emergence of REDD funds is thus consistent with the predictions of this paper. To reach the first-best, the above results state that all "marginal" forests with a conservation value must be preserved. One should thus pay to protect the areas that are just barely profitable to log, as well as those areas that would become profitable once the REDD policy is implemented and the timber price has increased.

The advice "buy coal" is justified in a simple benchmark model. I have abstracted from distributional issues (although a distributional argument favoring supply-side policies is presented by Asheim [2011]) as well as multiple practical issues. First, I have assumed away contract incompleteness and bargaining failures among the participants (analyzed in Harstad [2011, 2012*a*]). Second, I have ignored the coalition's incentive to delay paying for conservation (Harstad 2012*b*). Third, in reality, the emissions from exploiting 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. Fourth, a country may own unknown or potential deposits, and with some effort it can determine whether these contain fossil fuel. Since the incentive to search for new deposits is stronger if the fuel price is high, countries may search more if there is a deposit market. The effort to search is then suboptimally high since a nonparticipant does not internalize the environmental consequences if a new deposit is detected and exploited. Alternatively, a nonparticipant may gain from selling such a deposit even if it is not exploited and thus has no social value. In principle, the climate coalition has an incentive to either purchase potential deposits or pay nonparticipants for not searching. If such contracts cannot be made, the possibility of searching for new deposits would weaken the efficiency result above. Fifth, and relatedly, nonparticipants will invest too much in reducing their extraction costs unless the coalition can discourage such investments. Sixth, countries with hostile political environments may not be willing to loosen the grip on their territory. Or, 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 lease the deposits instead and simply pay the owner for not exploiting it right now. Future research should investigate the best role for deposit trading when these obstacles are taken into account.

Appendix

Proof of Proposition 1

Part *a:* Consider an equilibrium allocation of deposits, generating the cost functions $C_i(\cdot)$, and a stage 3 equilibrium with production levels x_i for all i. The x_i's constitute an equilibrium only if they solve each country's maximization problem:

$$\max_{x_i, y_i} B_i(y_i) - C_i(x_i) - p(y_i - x_i) \quad \forall i \in N,$$

$$\max_{p, x_M} B_M(y_M) - C_M(x_M) + p(x_M - y_M) - H(x_M + S(p)),$$

where I let M maximize with respect to p and x_M instead of, for example, y_M and x_M. In any case, (2)–(4) must be satisfied, implying

$$y_M = x_M + S(p) - D(p).$$

Now, take a small deposit of size Δ with marginal exploitation cost $c < p$, which implies that $i \in N$ would prefer to exploit it. By inserting (6) into (7), we get $B'_M(y_M) - H' \in C'_M(x_M)$, implying that M would prefer to exploit the deposit if and only if $B'(y_M) - H' \geq c$. Consider each case in turn.

If $c < B'(y_M) - H'$, the deposit will be exploited whether owned by i or M. If the right to exploit the deposit is transferred from i to M, i saves the extraction cost but loses some profit. For a given p, i's utility becomes

$$U_i = \max_{x_i, y_i} B_i(y_i) - C_i(x_i) - p(y_i - x_i) - (p - c)\Delta. \tag{A1}$$

We can use the envelope theorem to differentiate (A1), anticipating that p may be a function of Δ. When $\Delta \approx 0$,

$$\frac{dU_i}{d\Delta} = c - p - (y_i - x_i)\frac{dp}{d\Delta}. \tag{A2}$$

At the other end of the transaction, M's utility becomes

$$U_M = \max_{p, x_M} B_M(y_M) - C_M(x_M) - H(x_M + S(p)) + p(x_M - y_M) + (p - c)\Delta. \tag{A3}$$

Using the envelope theorem when differentiating (A3), we get simply[32]

$$\frac{dU_M}{d\Delta} = p - c. \tag{A4}$$

To summarize, the transaction increases $U_M + U_i$ if $(x_i - y_i)dp/d\Delta > 0$, as claimed by part *a* when $c < B'(y_M) - H'$. To see that $dp/d\Delta > 0$, consider the first-order condition when we maximize U_M in (A3) with respect to p:

$$[B'_M(y_M) - p][S'(p) - D'(p)] - H'(\cdot)S'(p) + (x_M - y_M) + \Delta = 0.$$

The left-hand side must increase in Δ and decrease in p when we require the second-order condition to hold. Thus, when Δ increases, p must increase for the first-order condition to be satisfied.

[32] The effect of Δ on y_M is zero: $y_M = x_M + \Delta + [S(p) - \Delta] - D(p)$. Intuitively, given p and x_M, where x_M is M's pretrade equilibrium production level, the transaction implies that i consumes the same but extracts Δ less whereas M extracts Δ more.

If $c \in [B'(y_M) - H', p]$, i would exploit the deposit, but M would not. If the deposit is transferred from i to M, i's payoff changes in line with (A2), as before.[33] For a given p, the nonparticipants' total supply changes from $S(p)$ to $S(p) - \Delta$. Thus, M's utility can be written as

$$U_M = \max_{p,x_M} B_M(y_M) - C_M(x_M) - H(x_M + [S(p) - \Delta]) + p\{D(p) - [S(p) - \Delta]\}, \quad \text{(A5)}$$

where

$$y_M = x_M + [S(p) - \Delta] - D(p).$$

Using the envelope theorem when differentiating (A5), we get simply

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

Thus, the transaction increases $U_M + U_i$ if $c - B'_M(y_M) + H' - (y_i - x_i)dp/d\Delta > 0$, as claimed by part a when $c \geq B'(y_M) - H'$.

Part b: For a third country, the transaction between M and i generates the additional benefit $(x_j - y_j)dp/d\Delta$, $j \in N\backslash i$, where $dp/d\Delta > 0$. To see whether the transaction is increasing $\sum_{M \cup N} U_i$, we simply have to add $\sum_{N\backslash i}(x_j - y_j)dp/d\Delta$ to the inequalities expressed in part a. QED

Proof of Lemma 2

If $i \in N$ is an exporter, then, according to proposition 1, i will sell any profitable deposit to M in equilibrium until i is no longer an exporter. This claim holds for every $i \in N$, and it follows that $x_M - y_M \geq 0$.

If i is an importer and sells a deposit with marginal cost $c < B'_M(y_M) - H'$ to M, then the sum of U_i and U_M declines according to proposition 1. Thus, $U_i + U_M$ increases from the reverse transaction. The reverse transaction is always possible since M is producing $x_M \geq y_M > 0$ using deposits satisfying $c < B'_M(y_M) - H'$. Hence, an importing country i buys deposits from M until i is no longer importing. In equilibrium, therefore, $y_i = x_i$ for all $i \in N$, implying that $y_M = x_M$. QED

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 satisfying $C'_i(x_i) = p$. Given the definition of $C'_i(x_i)$, it follows that $C'_i(\cdot)$ is continuous at x_i. Hence, we can find a sufficiently small deposit of size Δ, ordered to the left of x_i but sufficiently close to it, so that the marginal extraction cost of this deposit is $c < p$ but arbitrarily close to p, so that

$$c > p - H'(\cdot)\left[1 - \frac{S'(p)}{S'(p) - D'(p)}\right] = B'_M(y_M) - H',$$

where the last equality follows from (6) when $x_M = y_M$, as stated by lemma 2.

[33] We have $dp/d\Delta > 0$ for the same reason as before. In either case, the transaction implies that M ends up importing less, and it becomes optimal for M to set climate policies that generate a somewhat larger p.

According to proposition 1(*a*), when $x_M = y_M$, the sum $U_i + U_M$ increases if the right to exploit this deposit is transferred to *M*. Consequently, there exist some deposit prices making both *i* and *M* better off following the transaction, which contradicts that the initial allocation can be an equilibrium. QED

Proof of Proposition 3

Part *a:* From the objective function of $i \in N$ it follows that $\partial U_i/\partial r_j = (x_i - y_i)\partial p/\partial r_j$ if $i, j \in N$, $i \neq j$, whereas $\partial U_i/\partial r_i = p + (x_j - y_j)\partial p/\partial r_i$. Since r_M is maximizing U_M, we can write

$$U_M = \max_{x_M, y_M, r_M} \tilde{B}_M(y_M + r_M) - C_M(x_M) - H(x_M + S(p)) - p(y_M - x_M).$$

Using the envelope theorem, we get

$$\frac{\partial U_M}{\partial r_i} = [-H'(\cdot)S'(p) - (y_M - x_M)]\frac{\partial p}{\partial r_i} \quad \forall i \in N, \tag{A6}$$

so

$$\sum_{j \in M \cup N} \frac{\partial U_j}{\partial r_i} = p - H'(\cdot)S'(p)\frac{\partial p}{\partial r_i}.$$

To see that $\partial p/\partial r_i < 0$ for preinvestment policies, note that x_M and y_M are given at the investment stage and differentiate the first-order conditions $\tilde{B}_j'(y_i + r_i) = p$ and $x_j = S_i(p)$, together with the market-clearing condition, to get

$$(dy_j + dr_j)\tilde{B}_j'' = dp,$$

$$S_j'(p)dp = dx_j,$$

$$dy_i = \sum_{j \in N} dx_j - \sum_{j \in N \setminus i} dy_j.$$

By substituting the first two equations into the third and setting $dr_j = 0$ for all $j \in N \setminus i$, we can solve for $\partial p/\partial r_i$ to get

$$\frac{\partial p}{\partial r_i} = -\frac{1}{\sum_N [S_j'(p) - 1/\tilde{B}_j''(p)]} < 0. \tag{A7}$$

For postinvestment policies, $\partial p/\partial r_i < 0$ follows from the second-order condition when maximizing U_M with respect to *p*.

Consequently, if $S'(p) > 0$, socially optimal investments are given by

$$k_i'(r_i^*) = p - H'(\cdot)S'(p)\frac{\partial p}{\partial r_i} > p = k_i'(r_i).$$

Since $k_i(\cdot)$ is convex, the equilibrium investment level r_i is strictly smaller than the optimal r_i^*.

Part *b:* For preinvestment policies, simply substitute (A7) into (A6) to get (14). For postinvestment policies, it follows from the envelope theorem (when maximizing U_M with respect to x_M and *p*) that $\partial U_M/\partial r_i = \tilde{B}_M' - p$; combined with (6), we get (14). QED

Proof of Proposition 4

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

$$y_i = D_i(p) = \tilde{B}_i'^{-1}(p) - r_i \Rightarrow \frac{\partial y_i}{\partial p} = D_i'(p) = \frac{1}{(\tilde{B}_i'^{-1})'(p)} = \frac{1}{\tilde{B}_i''(y_i + r_i)}.$$

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 first-order condition, we get $dr_i/dp = 1/k_i''(r_i)$. Thus, demand is now given by

$$D_i(p) = y_i = \tilde{B}_i'^{-1}(p) - r_i \Rightarrow$$

$$D_i'(p) = \frac{\partial y_i}{\partial p} = (\tilde{B}_i'^{-1})'(p) - \frac{1}{k_i''(r_i)} = \frac{1}{\tilde{B}_i''(y_i + r_i)} - \frac{1}{k_i''(r_i)}.$$

QED

Proof of Proposition 5

I will first show how fuel prices depend on M's policy. In period 1, a price-taking $i \in N$ is indifferent whether to exploit a deposit with marginal extraction cost c if $p_1 - c = \delta(p_2 - c)$. Hence, the first-order conditions for $i \in N$ in period $t \in \{1, 2\}$, together with the market-clearing constraints, are as follows:

$$\begin{aligned} y_{i,t} &= D_{i,t}(p_t) = B_{i,t}'^{-1}(p_t), \\ x_{i,1} + x_{i,2} &= S_i(p_2) = C_i'^{-1}(p_2), \\ x_{i,1} &= S_i\left(\frac{p_1 - \delta p_2}{1 - \delta}\right) = C_i'^{-1}\left(\frac{p_1 - \delta p_2}{1 - \delta}\right), \qquad \text{(A8)} \\ \sum_N (x_{i,1} - y_{i,1}) &= I_1 \equiv y_{M,1} - x_{M,1}, \\ \sum_N (x_{i,2} - y_{i,2}) &= I_2 \equiv y_{M,2} - x_{M,2}. \end{aligned}$$

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. If we differentiate these equations, we get

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

By substituting the first three equations into the last two, we get

$$\sum_N \left[\left(\frac{dp_1 - \delta dp_2}{1-\delta}\right) S_i'\left(\frac{p_1 - \delta p_2}{1-\delta}\right) - dp_1 D_{i,1}'\right] = dI_1,$$

$$\sum_N \left[dp_2 S_i'(p_2) - \left(\frac{dp_1 - \delta dp_2}{1-\delta}\right) S_i'\left(\frac{p_1 - \delta p_2}{1-\delta}\right) - dp_2 D_{i,2}'\right] = dI_2.$$

Using the definitions $S_1' \equiv \sum_N S_i'((p_1 - \delta p_2)/(1-\delta))$, $S_2' \equiv \sum_N S_i'(p_2)$, $D_1' \equiv \sum_N D_{i,1}'(p_1)$, and $D_2' \equiv \sum_N D_{i,2}'(p_2)$, we can solve for dp_1 and dp_2:

$$dp_2 = \frac{dI_2 + dI_1 S_1'/[S_1' - D_1'(1-\delta)]}{S_2' - D_2' - \delta D_1' S_1'/[S_1' - D_1'(1-\delta)]},$$

$$dp_1 = \frac{dI_1(1-\delta)}{S_1' - D_1'(1-\delta)} + \delta \frac{S_1'}{S_1' - D_1'(1-\delta)} \left\{\frac{dI_2 + dI_1 S_1'/[S_1' - D_1'(1-\delta)]}{S_2' - D_2' - \delta D_1' S_1'/[S_1' - D_1'(1-\delta)]}\right\}.$$

At the policy stage, M chooses $\{x_{M,1}, y_{M,1}, x_{M,2}, y_{M,2}\}$ to maximize (15) for $i = M$. The first-order conditions for $x_{M,2}$ and $y_{M,2}$ become

$$-\left(1 - S_2' \frac{dp_2}{dI_2}\right) H' + p_2 + \frac{dp_1}{dI_2}\frac{I_1}{\delta} + \frac{dp_2}{dI_2} I_2 \in C_M'(x_{M,1} + x_{M,2}),$$

$$-\left(S_2' \frac{dp_2}{dI_2}\right) H' + B_{M,2}' - p_2 - \frac{dp_1}{dI_2}\frac{I_1}{\delta} - \frac{dp_2}{dI_2} I_2 = 0. \tag{A9}$$

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

$$\tau_{x,2} = \left(1 - S_2' \frac{dp_2}{dI_2}\right) H' - \frac{dp_1}{dI_2}\frac{I_1}{\delta} - \frac{dp_2}{dI_2} I_2,$$

$$\tau_{y,2} = \left(S_2' \frac{dp_2}{dI_2}\right) H' + \frac{dp_1}{dI_2}\frac{I_1}{\delta} + \frac{dp_2}{dI_2} I_2.$$

The first-order conditions for the first-period policy become[34]

$$-\delta\left(\frac{dp_2}{dI_2} - \frac{dp_2}{dI_1}\right) S_2' H' - (1-\delta) C_M'(x_{M,1}) + p_1 - \delta p_2$$

$$+ \frac{dp_1}{dI_1} I_1 + \delta \frac{dp_2}{dI_1} I_2 - \frac{dp_1}{dI_2} I_1 - \delta \frac{dp_2}{dI_2} I_2 = 0, \tag{A10}$$

$$-\delta\left(\frac{dp_2}{dI_1} S_2'\right) H' + B_{M,1}' - p_1 - \frac{dp_1}{dI_1} I_1 - \delta \frac{dp_2}{dI_1} I_2 = 0.$$

Suppose that the policy is implemented by taxes and profit-maximizing producers determine $x_{M,1}$. The marginal deposit exploited in period 1 is given by

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

When the last five equations are combined, M implements its first-period policy (A10) with the following taxes:

[34] Using the envelope theorem, we can ignore the effect of $x_{M,1}$ on $x_{M,1} + x_{M,2}$ since the first-order condition with respect to $x_{M,2}$ is equivalent to the first-order condition with respect to $x_{M,1} + x_{M,2}$.

$$\tau_{x,1} = \delta\left(1 - \frac{dp_2}{dI_1}S_2'\right)H' - \frac{dp_1}{dI_1}I_1 - \delta\frac{dp_2}{dI_1}I_2,$$

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

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 $\tau_{x,1}$. QED

Proof of Theorem 1(iii)

Lemma 2 holds for both periods and lemma 3 holds for the second period for the same reasons as before. Their proofs are thus omitted. With these lemmas, the optimal policy for period 2 under commitment, given by proposition 5, coincides with M's ideal policy once period 2 arrives, given by lemma 1. In either case, M relies only on supply-side policies (by setting, e.g., $\tau_{x,2} = H'$ and $\tau_{y,2} = 0$). It follows that $B_{M,2}' = p_2 = B_{i,2}'$ for all $i \in N$.

In the first period, M's policy is given by (A10) 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 5) when M can commit and $I_1 = I_2 = S_2' = 0$, this effect can be ignored (using the envelope theorem). In both cases, (A10) describes M's optimal policy for the first period. Substituting $I_1 = I_2 = S_2' = 0$ in (A10), we get $B_{M,1}' = p_1 = B_{i,1}'$.

Efficiency also requires that all extraction levels be socially optimal for both periods. In the second period, M extracts the optimal amount since (A9) implies $p_2 - H' \in C_M'(x_{M,1} + x_{M,2})$. A nonparticipant also extracts the optimal amount since every marginal deposit satisfying $c \in (p_2 - H', p_2)$ will be purchased by M, in line with the reasoning behind proposition 1. Regarding the extraction levels in the first period, dynamic efficiency requires $x_{i,1} = C_i'^{-1}((B_{j,1}' - \delta B_{j,2}')/(1 - \delta))$ for all i, j. This condition is identical to the equilibrium condition (A8) when $B_{j,1}' = p_1$ and $B_{j,2}' = p_2$. QED

Proofs of Lemma 4 and Theorem 1(iv)

These proofs follow the same steps as before and are available in Harstad (2010).

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