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Trading for the future: Signaling in permit markets

Bård Harstad [a,*], Gunnar S. Eskeland [b]

[a] Kellogg School of Management (MEDS), Northwestern University, 2001 Sheridan Rd., Evanston, IL 60208, USA
[b] Norwegian School of Economics and Business Administration, Helleveien 30, 5045 Bergen, and CICERO Center for International Climate and Environmental Research, Oslo, Norway

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ABSTRACT

Permit markets are celebrated as a policy instrument since they allow (i) firms to equalize marginal costs through trade and (ii) the regulator to distribute the burden in a politically desirable way. These two concerns, however, may conflict in a dynamic setting. Anticipating the regulator's future desire to give more permits to firms that appear to need them, firms purchase permits to signal their need. This raises the price above marginal costs and the market becomes inefficient. If the social cost of pollution is high and the government intervenes frequently in the market, the distortions are greater than the gains from trade and non-tradable permits are better. The analysis helps to understand permit markets and how they should be designed.

1. Introduction

We analyze a model where a planner, in each period, allocates a good according to some welfare function, after which the agents can trade these endowments in a market. The planner cannot commit to future allocation rules and it does not know the agents' types, but the pattern of trade may reveal some information. We derive the equilibrium allocation, the market equilibrium, and conditions under which the distortions in the market outweigh the gains from trade.

The model is not only of theoretical interest; but also is designed to resemble markets for pollution permits. Understanding permit markets is important since they are increasingly employed to regulate water use, fishing and pollution.[1] Since tradable permits were first analyzed by Crocker (1966), Dales (1968) and Montgomery (1972), the typical view has been that "in terms of production efficiency, the tradable quota system is equivalent to that of the Pigouvian tax" (Sandmo, 2000, p. 64). Moreover, the government can distribute the permits just as it pleases because the initial distribution does not affect the equilibrium allocation in a perfect market. Since tradable permits appear to combine the concern for efficiency with the government's concern for redistribution, it is celebrated as a policy instrument.

To date, the most extensive permit market is the Emission Trading System (ETS) for carbon dioxide in the European Union (EU). The ETS has a number of characteristics consistent with our model. First, the governments do distribute the permits periodically. The ETS was initiated in January, 2005, and permits were first distributed to more than 12,000 large point sources in 25 countries. By 2008, the governments distributed permits again, this time for a period of five years.[2] Second, the permits are, for the most part, distributed for free. In the first phase, national governments were obliged to distribute 95% of the permits for free, and only Denmark used the option of auctioning the remaining 5%. For the second phase, at least 90% of the permits had to be distributed for free, but in every country the fraction was higher. For the U.S. Clean Air Act, "Allowances were given to utilities rather than sold because there was no way that a sales-based program could have passed Congress" (Schmalensee et al., 1998, p. 56). Quite generally, Tietenberg (2006, p. 72) notes that: "free distribution of permits (as opposed to auctioning them off) seems to be a key ingredient in the successful implementation of emissions trading programs".[3] Third, when distributing the permits, governments rely on projections for future need, at least to some extent.

* Corresponding author. Tel.: +1 847 491 5166; fax: +1 847 467 1220.
E-mail addresses: harstad@northwestern.edu (B. Harstad), gunnar.eskeland@nhh.no (G.S. Eskeland).

[1] To fix ideas, we are consistently referring to pollution permits throughout this paper. For an overview of "individual transferable quotas" in fishing, see Hannesson (2004).

[2] In addition, "In some Member States a strong desire existed that if it turned out ex post that an installation needed more allowances or had reduced needs, the government would correct upwards or downwards the number of allowances allocated to such installations" (Zapfel, 2007, p. 32). Both Germany and the UK allowed for such ex post adjustments.

[3] Stavins (1998, p. 74–75) supports this: "when market-based instruments have been adopted in the United States, they have virtually always taken the form of tradeable permits rather than emission taxes"; "Moreover, the initial allocation of such permits has always been through free initial distribution, rather than through auctions".

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Summarizing the allocation process in the EU, Ellerman et al. (2007, p. 347) observe "projections became necessary because no Member State wished to deviate far from expected emissions in deciding the total to allocate to installations". In fact, the EU (Directive 2003/87/EC) *requests* that "Member States should have regard when allocating allowances to the potential for industrial process activities to reduce emissions". Fourth, governments do not directly observe the firms' needs. "The lack of data at the level of the installation was perhaps the biggest problem confronted in the allocation process by nearly all Member States" (Ellerman et al., 2007, p. 339).

This paper presents a simple multi-period model in which, in each period, the government distributes permits and the firms trade. The government cannot commit to future policies, implying that it distributes the permits just as it pleases in every period. With a concave social welfare function, the government prefers to distribute the permits for free, and it prefers to give more permits to firms that are likely to face high costs when reducing emissions. In reality, cost implications of emissions limits can determine whether firms go under, workers are laid off or production moves overseas. While the government does not observe the firms' costs directly, the pattern of trade reveals some information, and the government updates its beliefs accordingly. Naturally, "governments will inevitably find it hard to ignore the latest information on emissions" when distributing the permits.[4] Anticipating this, firms purchase more permits than what they would find optimal in a static setting, thereby signaling their need for permits. This raises the permit price above marginal costs, and the market ends up being distorted. Since only high-cost firms will signal successfully in equilibrium, high-cost firms pollute too much while low-cost firms pollute too little. We show that the distortions are larger if the period-length is short and the value of permits large. Thus, more important environmental problems require that the government commit not to intervene for a larger number of years. Otherwise, the distortions in the market can be so large that the gains from trade are at risk, and that it is better to abandon the market entirely and instead require uniform quotas. In sum: a combination of market and regulation can be worse than either alternative isolated.

There is not a lot of data due to the short history of tradable permits in practice, and many of the studies are based on experiments and simulations. These studies have suggested that the gains from trade are huge, with cost-savings that in some cases exceed 90% of the abatement costs compared to command-and-control (Carlson et al., 2000; Burtraw et al., 2005). Compared with observed abatement, however, Tietenberg (2006) finds that only parts of the estimated savings are realized. Our theory contributes to explaining this puzzle by indicating that the gains may be reduced by signaling costs. The problem has indeed been recognized in practice: Peter Zapfel (2007, p. 36) in the European Commission notes that "The downside of periodic allocation is that companies may adopt strategic behavior in order to maximize the number of free allowances to be allocated in future rounds".

Normatively, our analysis issues a warning to the combination of trade and a frequent redistribution of free pollution permits. The warning is more important for the EU's ETS, where each period has been only 3–5 years long. In the American sulfur dioxide market, on the other hand, the distributed allowances are long-lasting. While free, long-lasting permits may be provocative, based on our model, the U.S. market ought to be more *efficient* than the ETS. Our recommendations also conflict with the traditional view that frequent reallocation is beneficial to ensure flexibility.[5]

Our dynamic model breaks the aforementioned "equivalence" between tradable permits and Pigou taxes.[6] This way, we contribute to the literature on policy instruments in general[7] and the one on tradable permits, in particular.[8]

The literature on "grandfathering" emission rights rests on the assumption that the initial permit allocation is a direct function of historic emissions (e.g. Neuhoff et al., 2005). This makes it more attractive to pollute, the permit price increases, but presumes the market allocation is nevertheless efficient (Böhringer and Lange, 2005).[9] Our two contributions to this literature are to endogenize its key assumption and show that the efficiency result no longer holds. Unlike the literature on grandfathering, we do not *assume* that governments are backward-looking — that occurs in equilibrium since past emission is an indication of future needs. The pursuit for permits is then taking the form of signaling, creating distortions in the market and breaking the equivalence to a tax.

The paper also contributes to contract theory, in particular the literature on the "ratchet effect" (surveyed by Laffont and Tirole, 1993, Ch. 9). Like us, this literature assumes that the planner does not know the firm's type, and cannot commit to future actions. Laffont and Tirole motivate this by referring to incomplete contracts, while Freixas et al. (1985) suggest a commitment would not be credible, for example because the planner may be replaced. The planner provides an incentive scheme that may or may not separate the types. If the discount factor is large, separating two types becomes more costly since a firm anticipates that the incentive scheme may be altered when its type is revealed; pooling may then be cheaper for the planner. While our model of the firm is similar,[10] we relax the assumption that the planner fixes an incentive scheme. This is related to our timing, where the government acts before the types are realized. Instead, we allow for several firms and we let them trade the permits in a market. Firms anticipate the ratchet effect – that their action may influence future quotas – and this gives rise to a *market failure*. In contrast to the principal–agent literature, the planner cannot specify a finite menu (with only two choices), and the Intuitive Criterion implies that the market equilibrium is *always* separating. The temptation to pool the types in the traditional literature induces the planner to prohibit trading in our model.[11] Since our equilibrium is always in separating strategies, a multi-period model is more tractable than if the planner used incentive schemes. We can then show, for example, that the distortions in the market (i.e., the cost of separating the types) are larger if the types are highly correlated across time. This is conjectured, but left as an open question, by Laffont and Tirole (p. 414).

Our finding that a uniform quota allocation might be preferable to avoid costly signaling is also detected by Harstad (2007). That paper analyzes negotiations between districts and signaling generates delay.

[4] Quoted from Grubb and Neuhoff (2006, p. 16).

[5] For example, Noll (1982, p. 123) wrote that "reissuing permits…gives regulators continuing opportunities to adjust total emissions." For similar reasons, Åhman et al. (2007) recommend a 10-year cycle for permits.

[6] A commitment to uniform emission taxes (and no transfers to the firms) would implement the first best in our model, as will become clear below.

[7] See Baumol and Oates (1988) or Cropper and Oates (1992) for overviews. Buchanan and Tullock (1975) observed that it is more politically acceptable to distribute quotas for free, as this is viewed as less confiscatory. Also Bovenberg et al. (2005, 2008) assume that the government may want to compensate firms for the regulatory burden. If raising revenues lead to deadweight losses, the ranking of instruments can be affected and quotas may be preferred to taxes.

[8] While often presumed to be efficient and equivalent to a Pigou tax, permit markets may be inefficient if the permits are distributed non-cooperatively by multiple districts (Helm, 2003) or if some firms have market power (Hahn, 1984). The firms may then be able to collude and trade in a way that induces the government to issue a larger total number of permits in the next period (Andersson, 1997). Moledina et al. (2003) observe that the firms have incentives to raise the permit price to get more permits in the future, but they assume there are only two firms, no firm-specific uncertainty, and the government does not realize that firms are strategic.

[9] Exceptions arise if costs increase rapidly or the firms can borrow quotas over time (Rosendahl, 2008).

[10] Also Laffont and Tirole and Freixas et al. emphasize the model with two types and quadratic costs.

[11] Relatedly, Bisin and Rampini (2006) show how anonymous markets for capital help the government to implement time consistent tax policies. Anonymous markets would help also in our model, in principle, but when firms are trading the right to provide *public bads*, it is necessary that a regulator controls and monitors that emissions do not exceed the permits. This makes anonymous pollution markets less realistic in our setting.

In this paper, by contrast, signaling distorts the market. Furthermore, our model is dynamic and emphasizes the time inconsistency problem detected by Kydland and Prescott (1977). Thus, uniform policies are achieved only by abandoning the market.

The next section presents the two-period version of the model. Section 3 solves the model, and finds that while the last period implements the first best, the market may be distorted in the first. We derive simple conditions under which the distortions outweigh the gains from trade, such that non-tradable permits would be better. The distortions in the first period prevail if there are more periods; Section 4 shows that the results from the two-period model survive even if the number of periods is infinite. The model is deliberately kept simple, but Section 5 argues that it is robust to several generalizations. The final section concludes, while the Appendix contains all proofs.

2. The two-period model

2.1. The agents

There is a large number of similar firms, approximated by a continuum $I=[0, 1]$ of mass one. The gross profit of each firm $i\in I$ depends on a constant κ minus a quadratic cost of abating or reducing pollution, $\kappa-(\theta_i-x_i)^2/2$. A firm's type is given by θ_i, while x_i is i's level of pollution. With no restrictions on x_i, firm i would set $x_i=\theta_i$. θ_i can thus be interpreted as firm i's "business as usual" emission. Moreover, θ_i-x_i is not only firm i's abatement level, but also its marginal benefit of polluting or, equivalently, its marginal *cost* of abating or reducing pollution. A firm that has a "high cost" of reducing emission (large θ_i) prefers to pollute more.

To keep the model simple, $\theta_i\in\{\underline{\theta}, \bar{\theta}\}$ and $Pr(\theta_i=\underline{\theta})=k\in(0, 1)$ in period 1. The only linkage between the periods is that firm types are partially persistent: For each firm i, its type in the second period is stable, and thus the same as that in the current period, with probability $s\in(0, 1)$. With probability $1-s$, however, the firm's type is randomly drawn again (by Nature) with the same probability distribution as in period 1. Thus, if θ_i is i's type in period 1, its type in period 2 is θ_i^+, given by:

$$Pr\left(\theta_i^+=\underline{\theta}\right)=\left\{\begin{array}{l} s+(1-s)k \text{ if } \theta_i=\underline{\theta} \\ (1-s)k \text{ if } \theta_i=\bar{\theta} \end{array}\right\}. \quad (1)$$

Parameter k is therefore the fraction of low-cost firms in every period.

The timing in every period is given by Fig. 1. First, the government allocates permits, q_i, to the firms. The firms privately observe their types before deciding how much to pollute. If a firm chooses $x_i>q_i$, it must purchase x_i-q_i permits at the equilibrium market price p. If $x_i<q_i$, i can instead sell q_i-x_i permits. The firms cannot bank their permits from one period to the next.[12] Thus, firm i's net profit is given by

$$\pi_i=\kappa-\frac{1}{2}(\theta_i-x_i)^2+p(q_i-x_i).$$

While it is costly to abate, it is also costly to pollute. Instead of introducing citizens in the model, simply let the *owner* of firm i face a disutility vx of pollution, where x is the total mass of pollution and $v<\underline{\theta}$ is the value of clean air. The common discount factor is $\delta\in(0, 1)$. Letting the agents be risk neutral, each i seeks at time τ to maximize its expected discounted utility

$$u_i^\tau\equiv E\sum_{t=\tau}^{2}\left(\pi_i^t-vx^t\right)\delta^{t-1}.$$

[12] Relaxing this assumption would not change the results: Firms do *not* want to bank permits in equilibrium.

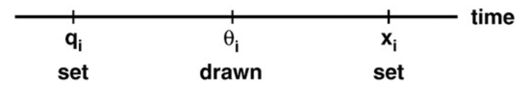

Fig. 1. Timing of events.

Parameters without subscript i represent the average and total value across the is, such that $x^t\equiv\int_I x_i^t di$ and $\theta\equiv k\underline{\theta}+(1-k)\bar{\theta}$.[13] Moreover, instead of always adding superscript t on the parameters, we use superscript "+" to label second period variables, and no superscript for the first period.

2.2. The planner

The government, or the central planner, seeks at every time t to maximize the Bergson–Samuelson welfare function $w(u_1^t, u_2^t, \ldots)$. We assume $w(.)$ is symmetric and strictly concave, i.e., the planner is egalitarian. Following the literature, and to avoid paternalism, the arguments of $w(.)$ are the *expected* discounted utilities of the agents.[14] An example of $w(.)$ is generalized utilitarianism, where the government would maximize $w(.)=\int\omega(u_i)di$.[15]

The government cannot commit to future policies, and we assume it distributes the permits for free. The latter assumption is empirically reasonable, as argued in the Introduction (and footnote 2); perhaps due to lobbying or other political constraints, although we do not model these constraints here. Moreover, the assumption can be relaxed, since the government would not benefit by selling or auctioning the permits in equilibrium. This becomes clear at the end of the next section.

2.3. The equilibrium concept

Together with the timing in Fig. 1, the game can easily be solved by backward induction. We look for a Perfect Bayesian Equilibrium (PBE), defined by a set of strategies for the firms, $x_i^t: H^t\to\mathbb{R}_+$, the government, $q_i^t: H^t\to\mathbb{R}_+\forall i\in I$ and beliefs $E\theta_i^t: H^t\to[0, 1]\forall i\in I$, where H^t is the set of possible histories at time t. To be a PBE, the strategies must be individually rational at every decision node, and beliefs must be consistent with Bayes' rule, whenever applicable.

Signaling games typically have a large number of PBEs, and we need refinements. In particular, we rule out equilibria that fail the Intuitive Criterion. Roughly, this implies that if the government observes an emission level $\tilde{x}$, and this can never be optimal for the low-cost type, then the government should conclude that the firm has instead high costs, if the high-cost firm, anticipating this conclusion, would have benefitted from emitting $\tilde{x}$.

Formally, for our two-type game we can restate the definition in Cho and Kreps (1987, p. 202) as follows. Let $u_*^\tau(\theta_i)$ be the expected equilibrium continuation payoff at time τ for a firm currently of type $\theta_i\in\{\underline{\theta}, \bar{\theta}\}$. Furthermore, let $u^\tau(\theta_i, \tilde{x}, E(\theta_i|\tilde{x}))$ be the set of possible expected continuation payoffs for type θ_i after taking the out-of-equilibrium action $\tilde{x}$, where $E(\theta_i|\tilde{x})\in[\underline{\theta}, \bar{\theta}]$ represents a possible subsequent belief, and where the other players play optimally given this belief. If there exists some τ and $\tilde{x}$ such that, for $\theta', \theta''\in\{\underline{\theta}, \bar{\theta}\}, \theta'\neq\theta''$,

$$u_*^\tau\left(\theta'\right)>\max_{E(\theta_i|\tilde{x})} u^\tau\left(\theta', \tilde{x}, E(\theta_i|\tilde{x})\right) \text{ and}$$
$$u_*^\tau(\theta'')<\min u^\tau\left(\theta'', \tilde{x}, \theta''\right),$$

then the equilibrium is said to fail the Intuitive Criterion.

[13] For such integrals to exist, we must assume the parameter is piecewise continuous in i. In equilibrium, it is always possible to order the is such that this is the case.

[14] If, instead, the arguments were the agents' realized utility, and w were a von-Neumann Morgenstern utility function, then the welfare function would not be Paretian since the planner may want to force the firms to take less risk (Hammond, 1981). This argument goes back to Diamond's (1967) critique of Harsanyi (1955).

[15] This particular form, where u_i is i's expected utility and $\omega''<0$, is recently justified and axiomatized by Grant et al. (2006).

This refinement generates a unique equilibrium; the least costly separating equilibrium. This equilibrium would survive and continue to be unique if we replaced PBE by sequential equilibria (Kreps and Wilson, 1982) or the Intuitive Criterion by D1 or D2 (for definitions of these concept, see Fudenberg and Tirole, 1996).

2.4. Robustness

Although our model is somewhat stylized to make the analysis simple and the results explicit, it is quite robust. While we start out with a two-period model, Section 4 shows that the results survive in the multi-period model. Section 5 discusses other robustness issues, and finds that the results continue to hold if the concavity of $w(.)$ is relaxed and replaced by (i) legislative bargaining or (ii) transaction costs. Furthermore, we discuss (iii) how to relax the Intuitive Criterion, (iv) commitment, (v) heterogeneity, and (vi) endogenous types. Despite all these possibilities to generalize, we have deliberately kept the model simple and reader-friendly.

3. The main results

3.1. The last period

In the last period, each i seeks to maximize u_i^+ or, equivalently, the profit π_i^+. The firm takes p^+ as given and purchases permits until its marginal benefit of polluting equals the permit price. This equalizes the marginal benefits (or costs) across firms, and is efficient.

Proposition 1. *No matter the initial distribution of quotas, in the last period marginal costs (2) are equalized across firms and the permit price is given by Eq. (3):*

$$\theta_i^+ - x_i^+ = p^+ \tag{2}$$

$$p^+ = \theta - q^+. \tag{3}$$

Notice that the allocation of the q_i^+s, given q^+, does not affect Proposition 1. This is in line with the Coase Theorem, and the 2nd welfare theorem, stating that the market equilibrium is efficient no matter the initial property rights. Tradable permits are celebrated for exactly this reason: “Because of this result, the management agency can distribute licenses as it pleases” (Montgomery, 1972, p. 409).

Given a strictly concave welfare function w, the government prefers to allocate the permits such as to equalize expected profits. This leads to the following initial distribution.

Proposition 2. *Given q^+, the government distributes the permits according to:*

$$q_i^+ = E\theta_i^+ + q^+ - \theta. \tag{Q}$$

In equilibrium, the government gives more permits to firms that are expected to have high costs. The reason for this is that these firms are going to pollute a lot, in equilibrium, and they would face a very low profit if they would have to purchase all the permits they need. Given the government's welfare function, it prefers an egalitarian distribution of the profits.

The initial allocation (Q) has a number of interesting properties. First, notice that it requests every firm to reduce its emission by the exact same amount $(\theta - q)$ compared to what i would be expected to pollute under business as usual. This leads to an expected profit loss of $p^2/2$, which is the same for every firm i. Thus, the expected burden is shared equally among all the firms. This is reasonable: “One often-invoked principle of equity is equality of sacrifice”, according to Joskow and Schmalensee (1998, p. 62).[16]

Furthermore, the expected marginal costs are equalized across the firms under (Q), and this is thus exactly the allocation the government would prefer if the permits were not tradable. Empirically, this cost-minimizing allocation is highly correlated with the actual allocation in the U.S. acid rain program: see Joskow and Schmalensee (1998, p. 61), who also argue that the cost-minimizing allocation “is of interest both because of actual and perceived market imperfections, and because autarchy was implicitly assumed in much of the actual debate about “fair” allowance allocations.” Also Noll (1982, p. 122) suggests that one “basis for the provisional allocation is the estimated competitive (cost-minimizing) allocation”.

The actual distribution following (Q) depends on the government's beliefs, and these are determined by Bayes' rule in equilibrium. If the equilibrium in the first period happens to be in separating strategies, the government would learn a firm's type θ_i in period 1, and use this information when calculating $E\theta_i^+ = s\theta_i + (1-s)\theta$. Substituted in (Q), we can derive the number of permits distributed to firms that had revealed themselves to have low and high costs. The difference, $\Delta \equiv \bar{q} - \underline{q}$, increases in the difference in types and the likelihood that the types will remain the same:

Corollary 1. *If the equilibrium is separating in the first period, the initial allocation is given by:*

$$q_i = \underline{q} \equiv q - s\left(\theta - \underline{\theta}\right) \text{ if } \theta_i^- = \underline{\theta}$$
$$q_i = \bar{q} \equiv q + s\left(\bar{\theta} - \theta\right) \text{ if } \theta_i^- = \bar{\theta}$$
$$\Delta \equiv \bar{q} - \underline{q} = s\left(\bar{\theta} - \underline{\theta}\right). \tag{S}$$

By substituting q_i^+ in u_i^+, it is straightforward to calculate the optimal q^+.

Proposition 3. *The government sets*

$$q^+ = \theta - v. \tag{4}$$

Combined with Eq. (3), we immediately get

$$p^+ = v. \tag{5}$$

In sum, the government is able to equalize the u_is in period 2 while, at the same time, the u_is are maximized since the market is efficient. In a one-period model, our analysis would end at this point, and we could confirm the presumption that tradable permits implement the first best. Tradable permits would also be equivalent to an emission tax of size v if the tax revenues were redistributed (uniformly or randomly).

3.2. The first period

Since the market equilibrium in the last period implements the first best, it is to hope that it coincides with the equilibrium also in the first period. Observing $x_i = \theta_i - p$ and p, the government would learn firm i's type. In the second period, the government would then distribute $\underline{q}$ and $\bar{q}$ to firms that had proven to have low and high costs.

Anticipating such an allocation, low-cost firms may be tempted to imitate the high-cost firms' strategy in the first period. If imitation is attractive, polluting $\bar{\theta} - p$ is not a sufficient proof of high costs. Instead, a high-cost firm must, to signal its type credibly, pollute more

[16] Similarly, Hahn and Stavins (1992, p. 466) argue that beyond cost-effectiveness, “other legitimate criteria of success should be considered, principal among these being the relative distributional equity or fairness associated with specific policies”.

than it would otherwise prefer, thereby separating itself from the low-cost firm.

By imposing the Intuitive Criterion, the equilibrium will, indeed, be in separating strategies. This implies that a low-cost firm is never going to persuade the government to believe that its cost is actually high, and it will thus set its marginal cost equal to the price of permits, such that $\underline{\theta}-\underline{x}=p$. High-cost firms pollute so much that the low-cost firms are just indifferent between $\underline{x}$ and imitation.

Proposition 4.

(i) *There is a unique equilibrium, which is in separating strategies.*
(ii) *The emission levels are given by Eq. (6) for low-cost firms and Eq. (7) for high-cost firms.*
(iii) *The permit price is given by Eq. (8).*

$$\underline{x} = \underline{\theta}-p \quad (6)$$

$$\overline{x} = \overline{\theta}-p + r/(1-k) \quad (7)$$

$$p = \theta-q + r, \text{ where} \quad (8)$$

$$r \equiv \max\left\{0, (1-k)\left(\sqrt{2\delta\Delta p^{+}}-\left[\overline{\theta}-\underline{\theta}\right]\right)\right\}, \text{ therefore :} \quad (9)$$

$$r > 0 \text{ if } 2\delta\Delta v > \left(\overline{\theta}-\underline{\theta}\right)^2. \quad (C)$$

Ideally, a high-cost firm would prefer to pollute only $\overline{\theta}-\underline{\theta}$ units more than the low type, and still gain the value $\delta\Delta p^{+}$ of Δ more permits, at the price p^{+}, discounted by the factor δ since they are received only in the future. For the low type, the cost of imitating this strategy is $(\overline{\theta}-\underline{\theta})^2/2$, and if this cost is larger than the gain $\delta\Delta p^{+}$, the types separate and there is no need for the high-cost type to distort its emission. But if $(\overline{\theta}-\underline{\theta})^2/2<\delta\Delta p^{+}$, low-cost firms are tempted to imitate, and to credibly signal a high cost, firms need to pollute so much that imitation is too costly for low-cost firms. This requires $(\overline{x}-\underline{\theta})^2/2\geq\delta\Delta p^{+}$, which gives condition (7). Thus, the larger is $\delta\Delta p^{+}$, the more the high-cost firms must pollute to signal credibly. This raises demand for permits, and therefore the price, which ends up being larger than the average marginal cost. Buying permits has a "reputational value", r, which together with the average marginal cost sums to the equilibrium price.

By combining Eqs. (6)–(7),

$$(\underline{\theta}-\underline{x})-(\overline{\theta}-\overline{x}) = r/(1-k).$$

Thus, in addition to measuring the distance between p and the *average* marginal cost $\theta-q$, r also measures the *difference* in marginal costs. Ideally, marginal costs should be equalized, so r captures how much the market is distorted.

Substituting (S) and Eq. (4) in Eq. (9), we can calculate r:

$$r \equiv \max\left\{0, (1-k)\left(\sqrt{2\delta vs\left(\overline{\theta}-\underline{\theta}\right)}-\left[\overline{\theta}-\underline{\theta}\right]\right)\right\}, \text{ therefore}$$

$$r > 0 \text{ if } 2\delta vs > \overline{\theta}-\underline{\theta}.$$

If types are stable (s large), today's high-cost firms receive many more permits in the future (Δ large). If the problem is severe (v large), the future permit price is high and the value of getting more permits large. The present discounted value of more permits is large if the future is close (δ large). Large v, s and δ are therefore making it more likely that the high-cost firms distort their emission levels and, if they do, the distortions are greater.

It only remains to calculate the optimal policy in period 1. When the government has no information about the firms' types, the u_is are equalized by uniform quotas, $q_i=q$. These quotas, in turn, should be set such that expected marginal costs equal the value of abatement:

Proposition 5. *In period 1, the optimal number of permits is*

$$q = \theta-v. \quad (10)$$

The total number of permits is thus the same in both periods, even if trade is distorted in period 1 while being efficient in period 2.[17]

Substituting the optimal q into the price function (8), we can state the optimal policy in terms of the price instead of the quantity:

Corollary 4. *In period 1, the optimal price of permits is given by:*

$$p = v + r. \quad (11)$$

Thus, $p>v$ whenever (C) holds. The intuition is straightforward: If the market for permits is distorted, the equilibrium price is higher than the average marginal cost of reducing pollution. The latter should be equal to the marginal value, v, which thus must be less than the equilibrium price. It is therefore wrong, although typically presumed, that the number of quotas should be such that the price reflects the social value of cleaning. The price is excessively high because of the reputational effect, and it should thus be *higher* than the value of cleaning.

3.3. A market or plan for permits?

The distortions in the market for permits suggest that trade in permits may not be as efficient as previously thought. But how large are these distortions, and how important is this problem? Addressing these questions, we now compare the distortions to the gains from trade, and find conditions under which prohibiting trade is actually better.

In the last period, the market is efficient and implements the first best. This is obviously not true if quotas are non-tradable, since the government does not know the realized types when distributing the quotas. Thus, trade is always recommended for the last period. The first period market is distorted, however, if (C) holds. In fact,

Proposition 6. *If (C) holds, there is too much trade in permits.*

It is easy to show that the optimal q is given by Eq. (10), even if the permits are not tradable.[18] When allocating the permits in the first period, the government has no information about the firms, and it prefers to give everyone the same number of permits. Since $\overline{x}>\underline{x}$ in equilibrium, high-cost firms have to buy permits from low-cost firms. Prohibiting trade prevents low-cost firms from *optimally* selling their permits to high-cost firms. But it also prevents high-cost firms from costly signaling their types.[19] When can it be that the costs of signaling (area A in Fig. 2) outweigh the gains from trade (area B)? The condition turns out to be simple and intuitive.

Proposition 7. *Permits should be tradable if and only if:*

$$2(\overline{\theta}-\underline{\theta})^2\geq\delta\,\Delta p^{+}. \quad (12)$$

[17] Although the total cost of cleaning (for each q) is larger in period 1, the *marginal* cost with respect to q is the same. This is due to the quadratic profit function, and it simplifies the comparison to non-tradable permits in the next section. In general, the optimal q could be larger or smaller if trade is allowed or if trade is inefficient. This would depend on the profit function.

[18] Simply maximize $\kappa-k(\underline{\theta}-q)^2/2-(1-k)(\overline{\theta}-q)^2/2-\nu q$ w.r.t. q.

[19] The result that there will be too much trade holds because the equilibrium is in separating strategies, which is due to the Intuitive Criterion. Without that, Section 5.3 argues that the equilibrium can be in pooling strategies, implying too little trade, while the other results of the paper continue to hold.

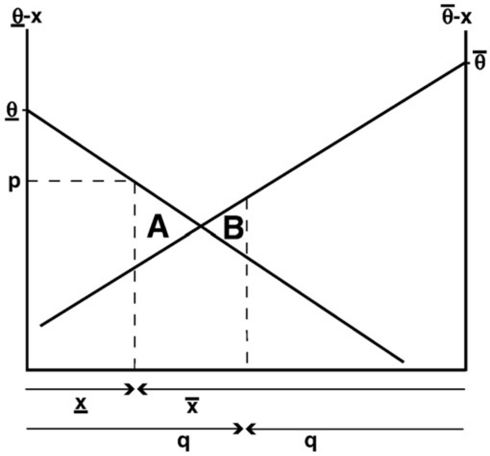

Fig. 2. If the social cost of signaling (A) is larger than the gains from trade (B), trade should be prohibited (the figure presumes $k=1/2$).

If (C) does *not* hold, trade is first-best and Eq. (12) always holds. Otherwise, $r>0$ and the market is distorted. That is, of course, not a sufficient condition for prohibiting trade. The distortions from signaling must be compared to the cost of non tradable uniform emission quotas, and this gives condition (12).

Substituting (S) and Eq. (5) in Eq. (12), trade is good if and only if

$$2(\overline{\theta}-\underline{\theta})\geq \delta s v.$$

The cost of uniform quotas is, naturally, increasing in the heterogeneity $(\overline{\theta}-\underline{\theta})$, making trade relatively better. But the incentives to signal high costs increase in δ, s and $p^{+}=v$, and so do the distortions from trade. Thus, if the future is close (δ large), the types stable (s large) and the future value of permits (v) high, it is very tempting to signal high costs and the resulting distortions are higher than the cost of uniform standards. Therefore, trade is good only if $(\overline{\theta}-\underline{\theta})$ is large while δ, s and v are small. Note that if the problem is more important (in that v is large), permits should *not* be tradable.

Remark. While we have assumed that the government compensates high-cost firms in the form of more permits, the results would be identical if the compensation took the form of cash or some other good instead. As is clear from our analysis, it is the *monetary value* of Δ that generates the distortions, not the quotas per se. If e.g. the government would sell the permits, it would prefer to redistribute the revenues such as to equalize the u_is, the optimal price would be $v+r$ and the subsequent market would be inefficient under (C). Moreover, since there is no private information in equilibrium at the time when the government allocates the permits, it cannot benefit from using another allocation method or incentive scheme.

4. Multiple periods

The two-period model can easily be extended to an infinite number of periods. Superscript "+" and "−" are added to all parameters representing the next and the previous period, respectively (this way, we do not need superscripts for periods). Firm types follow the Markov process (1) where firm i is low-cost with a probability that depends on its type in the previous period. While the model itself can stay unchanged, the equilibrium concept must be refined. In dynamic games, as in repeated games, there are typically a large number of equilibria (based on various "Folk theorems"), even when restricting attention to PBEs satisfying the Intuitive Criterion. As is common, we restrict attention to Markov Perfect Equilibria (as defined by Maskin and Tirole, 2001). This implies that firms' strategies depend on the history only to the extent it is reflected in today's total number of permits, q.[20]

A firm's problem is then quite simple. Just as in Section 3.2, a firm maximizes current profit, only taking into account how its decisions affect the government's beliefs for the following period. This problem is solved in the proof of Proposition 4, which continues to hold.

Since the firms' strategies do not depend on the q in any earlier period, the government chooses q understanding that its level will have no impact on future periods. The optimal q is thus just as derived in Proposition 5, which continues to hold. Propositions 6 and 7 continue to hold as well, since their proofs build on Propositions 4 and 5.[21] To summarize:

Proposition 8. *In every period, the equilibrium* $\underline{x}$, $\overline{x}$, *p and q are given by Eqs. (6), (7), (8) and (10), respectively. Propositions 4–7 continue to hold.*

In contrast to the two-period model, the infinite period model generates distortions in *every* period. Thus, in a given period, the future price is given by $p^{+}=v+r$ rather than by $p^{+}=v$ as in the two-period model. p is a function of r, which is a function of p^{+}. It turns out to be a unique fixed point for p.

Proposition 9. *There are unique equilibrium values for* $p=p^{+}$ *and r, where p is given by* $p=v+r$ *and r is given by:*

$$r=\max\left\{0,(1-k)\left(\sqrt{2\delta\Delta v-\left(\overline{\theta}-\underline{\theta}\right)^{2}+\left[\overline{\theta}-\underline{\theta}-\delta\Delta(1-k)\right]^{2}}-\left[\overline{\theta}-\underline{\theta}-\delta\Delta(1-k)\right]\right)\right\}$$
$$>0 \text{ if } (C) \text{ holds.} \tag{13}$$

The condition for $r>0$ is, again, given by (C). Moreover, r increases in δ and Δ but decreases in q, $(\overline{\theta}-\underline{\theta})$ and k, just as before.[22] But if (C) does hold, r and p are larger than in the two-period model. The reason is that if e.g. v is so large that the reputational value of purchasing permits is positive, it increases r directly and thus p, but it also increases p^{+} and then, again, r. If there are distortions, these are greater than when there were only two periods.

So far, this section has taken Δ as given. This was possible, since all results in Section 3.2 were presented as if Δ were a primitive. Of course, Δ is endogenous and, in the two-period model, it was given by Eq. (S). Is that so, also in the infinite period model?

When the government maximizes w by distributing the permits, it prefers to equalize expected profits, conditional on its beliefs about the firms' types. Moreover, the government's expectation of the profits depends on its understanding of the market. One may argue that the government should have rational expectations, taking into account the distortions that are going to take place. On the other hand, one of the claimed contributions of the present paper is pointing to these distortions. Thus, one could also argue that the government is

[20] Historic levels of q or x_i are not "payoff relevant" in that they do not affect a firm's relative preference for any future x_i, taking as given the other players' future x_j and q. Even the government's beliefs are not payoff relevant when, in line with the proof of Proposition 4, the unique equilibrium is in separating strategies.

[21] It is only the proof of Proposition 6 that needs a minor modification, since the quotas are not distributed uniformly when the equilibrium was separating in the previous period. By letting "$\overline{x}^{*}>\max\{\underline{q},\overline{q}\}$" replace "$\overline{x}^{*}>q_i=q$", the proof continues to be true.

[22] This is most easily seen by writing.

$$r=\max\left\{0,(1-k)\left(\sqrt{w+y^{2}}-y\right)\right\}, \text{where}$$
$$w\equiv 2\delta\Delta v-(\overline{\theta}-\underline{\theta})^{2} \text{ and}$$
$$y\equiv\overline{\theta}-\underline{\theta}-\delta\Delta(1-k).$$

Clearly, r increases in w but decreases in y, giving the comparative static discussed above. Under (S), however, one can show that r is hump-shaped in $(\overline{\theta}-\underline{\theta})$, such that r increases initially in $(\overline{\theta}-\underline{\theta})$: When the heterogeneity is very small (and approaching zero), $\Delta=s(\overline{\theta}-\underline{\theta})$ makes r small (and approaching zero).

naive and does not anticipate any distortions (as in Moledina et al., 2003).

Proposition 10. *(i) If the government expects the market to be efficient, $\Delta = s(\overline{\theta} - \underline{\theta})$ as in Eq. (S). (ii) If the government has rational expectations, Δ is equal to ($\tilde{S}$) below.*

$$\Delta = s\left[\left(\overline{\theta} - \underline{\theta}\right) + \frac{r^2}{2(v+r)(1-k)^2}\right] \tag{$\tilde{S}$}$$

Rational expectations increase Δ when $r>0$, since the egalitarian government prefers to compensate the high-cost firms also for the costs of signaling. Anticipating the larger Δ, the temptation to signal high costs increases and the market becomes even more distorted. Since r increases in Δ, which in turn increases in r, the comparative statics, discussed above, are strengthened. It is still true, for example, that a larger v makes it more likely that non-tradable permits are better, as in Proposition 7, but with rational expectations in the dynamic model, it is *even more* likely that non-tradable permits are good, for any given v.[23]

5. Robustness and extensions

5.1. Legislative bargaining

Above, we assumed the government's social welfare function w were strictly concave. This motivated the egalitarian distribution of the q_is and thus $\Delta>0$. It is easy to endogenize the government's preference for an equal distribution of utilities. Take a political economy approach, for example. Instead of assuming a single egalitarian decision-maker, let each firm be represented by a legislator, negotiating on its behalf (like in Joskow and Schmalensee, 1998).[24] The legislators negotiate every policy discussed above (such as q, the q_is, and whether permits should be tradable). Suppose the legislators have no private information on the firms' types, and let the outcome be characterized by the Nash bargaining solution, where the default outcome is no regulation.

Proposition 11. *Assume policies are determined by legislative bargaining rather than an egalitarian benevolent planner. Every result above continues to hold.*

5.2. Market imperfections and transaction costs

Our results are stated in terms of Δ, and they hold for any $\Delta \geq 0$, even if the specification (S) is not satisfied. Thus, the results are quite general and consistent with various reasons for why the government prefers to give more permits to high-cost firms. In addition to an egalitarian government, or legislative bargaining, there are other reasons to expect $\Delta \geq 0$.

Suppose the government is utilitarian, such that it simply maximizes the sum of utilities. Then, the initial distribution of the permits, the q_is, does not seem to matter for the government. "Not so, potentially, in the presence of transaction costs", is the reply of Stavins (1995, p. 143). Hahn and Stavins (1992, p. 465) notice that "transaction costs in tradable permit markets can be substantial", creating an "efficiency justification for politicians' typical focus on initial allocation" (Stavins, 1995, p. 133). For the US SO_2 market, Carlson et al. (2000, p. 1319) found that "many participants opted out of the market". To capture such market imperfections in a simple way, assume that, with probability $\epsilon>0$, $\epsilon \to 0$, a firm does not participate in the permit market. Segal (1999, p. 340) uses a similar assumption and suggests the offer "may be lost in the mail." Alternatively, managers may be time or credit-constrained, they may not succeed in matching with a buyer/seller, or the mere transfer of permits could entail prohibiting transaction costs. To simplify further, assume that firms cannot *pretend* they were unable to find a trading partner.

Proposition 12. *Suppose w is utilitarian but, with probability ϵ, $\epsilon \to 0$, firms do not trade. Propositions 1–9 continue to hold and the initial allocation is given by (Q) and (S).*

While a utilitarian government would be indifferent to the initial allocation of the q_is in a perfect market, small imperfections break the tie. With even the slightest chance that the firms will not trade, it is strictly preferable for the government to allocate the permits such that expected marginal costs are equalized. This gives the initial allocation (Q), which implies (S), since the firms' strategies remain the same. Thus, (S) holds whether the number of periods is two or infinite, no matter whether the government has rational expectations or believes the firms will trade non-strategically.

5.3. Pooling

Our unique equilibrium, and the result that it is in separating strategies, rely on the Intuitive Criterion. Imposing this criterion may be reasonable, particularly because we otherwise would have a very large number of equilibria.[25] In particular, without imposing the Intuitive Criterion, one may have equilibria in pooling strategies where every firm pollutes the same amount. This can be supported if the government interprets any deviation as evidence of low cost. Low-cost firms are then willing to pollute just as much as high-cost firms, since they otherwise would be given smaller quotas in the future. In this equilibrium, Proposition 6 would be reversed: There would be *too little* trade. However, the other results would survive, qualitatively: The market for permits is distorted and not efficient, and this is more likely to happen if the permits are distributed frequently (such that δ and s are high). If we stick to the two-period model, it is easy to investigate when a pooling equilibrium exists in the first period:

Proposition 13. *Relaxing the Intuitive Criterion, a pooling equilibrium exists with $x_i = q_i = \theta - v$ and no trade if and only if:*

$$\delta s v \geq \frac{\overline{\theta} - \underline{\theta}}{8(1-k)}. \tag{14}$$

The intuition is as before: If the problem is important (v large) while the stability of types and the discount factor are large, low-cost firms are getting far less quotas in the next period, the value of future permits is large and the future is important. In these circumstances, firms are reluctant to reveal low costs, and the market is thus distorted. If heterogeneity is sufficiently large, however, it is too costly for different firms to pool on the same strategy. Proposition 13 does not specify the price p, since there may be a range of prices supporting the pooling equilibrium.

[23] Although r is a function of Δ, $r(\Delta)$, and Δ is a function of r, $\Delta(r')$, r is still not exploiding because the composite function, $r(\Delta(r'))$, has the derivative $\delta s/2<1$ in the limit as $r' \to \infty$.

[24] Tietenberg (2006, p. 129) writes that "negotiation was an important element" of the US Sulfur Allowance Program. In the EU, "the allocation process can best be described as an extended dialogue between the government and industry" (Ellerman et al., 2007, p. 344).

[25] Nevertheless, the Intuitive Criterion is sometimes criticized because it implies that high-cost firms undertake costly signaling even when almost all firms have high cost (see e.g. Bolton and Dewatripont, 2005, p. 110). For this reason, the separating equilibrium in e.g. Spence's (1973) labor market may be Pareto-dominated by a pooling equilibrium where no-one undertakes costly education. This critique, however, has no bite in the present model: By combining Eq. (6)–(C) and Eq. (10), as $k \to 1$, $r \to 0$, and almost all firms pollute optimally. Similarly, as $k \to 0$, $\overline{x} \to \overline{\theta} - v$, and almost all firms pollute optimally.

5.4. Commitment

The key assumption in our analysis is that the government cannot commit to future allocations of the quotas. Then, whenever the government has the slightest concern for fairness, transaction costs or the representatives' bargaining power, more permits are given to high-cost firms. If the government is distributing the permits frequently, this creates distortions in the market.

But what if the government can commit? It may write statutes or domestic laws specifying how the permits ought to be allocated in the future as an arbitrary function of the history. It may also be bound by international climate agreements. If the government can commit to future allocation rules, it is much easier to obtain efficiency.

In particular, take the legislative bargaining model in Section 5.1, and suppose the legislators, before learning anything about their local firm, commit to the uniform rule $q_i = q$ no matter what should happen subsequently. Since firms cannot affect their future q_is, they maximize current profit as in Section 3.1. The market is efficient and, to maximize expected utility, every legislator agree on $q = \theta - v$. The first best is thus implemented. Note, however, that the rule does require pre-commitment. After a legislator learns that its local firm has a high cost, it is tempted to initiate renegotiation and demand more permits.

With commitment, the first best is also easily implemented for the model in Section 5.2, where there are tiny market imperfections and a utilitarian government. By committing to $q_i = q$, the market is efficient unless it, with probability ϵ, fails to work. The sum of expected utilities is also maximized, so the first best is achieved in the limit as $\epsilon \to 0$.

However, if the government is egalitarian, as in Sections 2–4, it is not satisfied with a uniform distribution of quotas after learning that the expected costs do vary. The first best, in this situation, requires both efficiency *and* that expected profits are equalized across firms. Efficiency requires low and high-cost firms to pollute $\underline{x}^* = \underline{\theta} - v$ and $\overline{x}^* = \overline{\theta} - v$. Equalizing expected profit requires such firms to be rewarded with $\underline{q}$ and $\overline{q}$ in the next period. In Section 3, the prospects of $\overline{q}$ induced high-cost firms to pollute more than optimal. Suppose the government commits to not reward such behavior and, instead, that it allows the firm to only pollute $\underline{x}^*$ or $\overline{x}^*$. As explained above, this is *not* separating the types if the permit price is $p = v$ when (C) holds. Low-cost firms are then induced to imitate the high-cost firms by polluting $\overline{x}^*$. When $q = k\underline{x}^* + (1-k)\overline{x}^*$ is given, this increases the market price for permits until the point at which no low-cost firm find it attractive to imitate high-cost firms.

At this price, neither type sets marginal costs equal to the price, and it is thus crucial that the firms are indeed unable to choose emissions different from $\{\underline{x}^*, \overline{x}^*\}$.[26]

Proposition 14. *If the government can commit, the first best is implemented by the following allocation rule:*

$$\text{If } x_i^- = \underline{x}^* = \underline{\theta} - v, q_i = \underline{q}$$
$$\text{If } x_i^- = \overline{x}^* = \overline{\theta} - v, q_i = \overline{q}.$$

The equilibrium price is any

$$p \in \left[\frac{v - \left(\overline{\theta} - \underline{\theta}\right)/2}{1 - \delta s}, \frac{v + \left(\overline{\theta} - \underline{\theta}\right)/2}{1 - \delta s} \right].$$

It is easy to see that if (C) holds, $p > v$. Thus, the equilibrium price must still be larger than the social marginal value of abatement and the private marginal cost of abating, under the very same condition as before. Imitation is unattractive for the low type only if the price is above the lower threshold. At the upper threshold, the price is so high that it is actually the high-cost type that prefers to imitate the low-cost type. Any price between these thresholds satisfies both types' incentive constraints and the equilibrium is separating. When δ and s increase, both thresholds for p become larger, and p must increase, just as before.[27]

5.5. Heterogeneity

Throughout this paper we have assumed that firms are identical, except for their type θ_i. However, allowing for observable heterogeneity in e.g. κ would not affect the results. Moreover, suppose that k were known to vary across firms. Then, $\overline{q}$ and $\underline{q}$ may as well vary across firms and should be written $\overline{q}_i$ and $\underline{q}_i$. The results above would be identical if just $\overline{q}_i - \underline{q}_i$ were the same for all firms. This would actually be the case (using (Q)), implying that Eq. (S), and thus all the results, would continue to hold. If firms were of different sizes, to give another example, we could simply let the profit function and all the variables above be measured per unit of capital (or firm size). The results above would be unaffected.

We have also simplified by assuming each firm to be associated with exactly one owner. More generally, one could let α_{ij} measure individual i's ownership of firm j. As is easy to show, all results continue to hold if just $\sum_i \alpha_{ij} = \sum_j \alpha_{ij} = 1$.

5.6. Endogenous types

While firm types are exogenous in our model, endogenizing θ_i would strengthen our results. Suppose that firm i can make some investment that affects its probability of becoming a low-cost firm. A successful investment implies that the firm is penalized in the form of a smaller initial quota, with an immediate effect if the outcome is observable. Thus, the firm has too low incentives to reduce its cost of cleaning or, equivalently, it has too high incentives to pollute. The more frequently the government intervenes, the more these incentives are distorted (as in Pint, 1992).

6. Conclusions

Tradable pollution permits are celebrated as a policy instrument. They supposedly combine the efficient features of a market with the government's concern for the distributive impacts. We show, however, that these two goals conflict in a dynamic setting when we take political constraints into account. Anticipating the government's concern for redistribution, the permit price is above marginal costs of cleaning, and trade is distorted. The distortions are larger if the government redistributes frequently and if the value of the permits is large.

To be precise, let T be the number of years within each period, meaning that the government redistributes permits only every T year. Parameter v measures the social value of reducing emission. Our main results are illustrated in Fig. 3: Trade is first-best in area *FB*, while in area *DIST*, there is distorting signaling. Since the curves are upward-sloping, Fig. 3 shows that if v is larger, T must be larger to prevent distortions. In words, for important environmental problems, the government should commit to not intervene in the market for a larger number of years. Otherwise, we may enter area *BAD* where the

[26] The proposition assumes that any $x \neq \{\underline{x}^*, \overline{x}^*\}$ is prohibitively costly. However, if the government can only threaten to give *zero quotas* after such a choice, we should also add an incentive constraint for each type to ensure it does not prefer to maximize static profit by setting $x_i = \theta_i - p$. One can show that these incentive constraints do not bind if θ is sufficiently large.

[27] In principle, the government may want to commit by using particular benchmarks for calculating the initial allocation. In practice, however: "In no aspect of the allocation process for the EU ETS was the disparity between advocacy and practice greater than for benchmarking" (Ellerman et al., 2007, p. 351). This suggests that commitments were not that easy, after all.

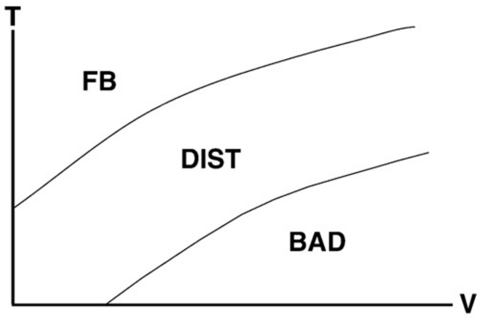

Fig. 3. The larger the value of cleaning, v, the larger the period-length, T, should be.

distortions are larger than the gains from trade, and it is actually better to prohibit trade.[28]

Theoretically, the analysis provides lessons for the old debate on plan versus markets. While a perfect market would be first-best in our setting (with no redistribution), frequent intervention distorts the market allocation. The more often the government intervenes, the worse the market performs. At some point, it is better to abandon the market altogether and rely completely on command-and-control, prohibiting trade in permits. This suggests that efficiency, as a function of regulatory intervention, may be U-shaped. Mixing plan and market might be worse than either. Our analysis also illustrates that the first and the second welfare theorems may conflict in a dynamic setting.[29]

But the analysis is not only of theoretical interest. Permit markets are used for fish catch and various environmental problems. Currently, they are becoming increasingly important in mitigating global climate change, and it is thus immensely important to understand the dynamic effects of such markets. Our model is consistent with several features of the ETS market in the EU. As documented in the Introduction, governments do distribute the permits periodically, they are typically distributed for free, projections are used but the government has imperfect information on future needs. Based on these features, our model explains why the market for permits may not be as efficient as previously thought. More recently, the EU has recommended to use auctioning to a larger extent, consistent with the policy recommendations of this paper.

Of course, our simple framework has many shortcomings. Empirically, the model's predictions should be tested when more data becomes available. Theoretically, we have simply assumed a benevolent government, and we have not formalized why the government is unable to commit to future policies. Future research should formalize how voters and the political institutions determine the politicians' preferences and their possibilities to commit. Deriving optimal and equilibrium policies, given these constraints, may bring us closer to the best possible environmental regulation.

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Appendix A. Appendix: Proofs

Proof of Proposition 1. At $t=2$, each i solves

$$\max_{x_i^+} \kappa - \frac{1}{2}\left(\theta_i^+ - x_i^+\right)^2 + p^+\left(q_i^+ - x_i^+\right) - vq^+.$$

While the second-order condition is trivially fulfilled, the first-order condition is

$$\theta_i^+ - x_i^+ = p^+ \Rightarrow \int_I \left(\theta_i^+ - x_i^+\right) di = \theta - q^+ = \int_I p^+ di = p^+. \tag{A.1}$$

A firm or individual cannot affect the total level of emission, since $x^+ = q^+$.

Proof of Proposition 2. At the beginning of period 2, the government maximizes w by choosing $q_i^+ \forall i \in I$, anticipating that Eq. (2) implies $\pi_i^+ = \kappa + (p^+)^2/2 + p^+(q_i^+ - \theta_i^+)$. The problem can be solved in two stages, first by choosing the q_i^+s given q^+ (thereafter by choosing q^+). The optimal q_i^+s must solve:

$$\max_{\{q_i\}} w\left(\left\{E\pi_i^+ - vq^+\right\}_i\right) s.t. \int_I q_i^+ di = q^+.$$

Since every $(\partial w/\partial(E\pi_i^+))p^+$ must equal the Lagrange multiplier and w is symmetric, it follows that $E(\theta_i^+ - q_i^+)$ must be the same for all is. Since they must sum to $\theta - q^+$, (Q) follows.

Proof of Proposition 4. We first prove (ii). *If* the equilibrium is separating, a low-cost firm does not want to imitate high-cost firms and it will receive $\underline{q}$ in the next period. Since a firm can never get *less* than $\underline{q}$ under (Q), low-cost firms must pollute such that:

$$\underline{x} = \arg\max_x \left(p(q-x) - \left(\underline{\theta} - x\right)^2 / 2 + \delta \underline{q} p^+\right) = \underline{\theta} - p.$$

Let $\overline{x}$ represent the equilibrium pollution level of a high-cost firm. The pair $(\underline{x}, \overline{x})$ *fails* the Intuitive Criterion (for its general definition, see Cho and Kreps, 1987) if there exists another alternative x' which is (i) *always* worse for the low-cost firm (even if it should lead to a quota $\overline{q}$ in the next period), but (ii) strictly *better* for the high-cost firm if just the government believes $E(\theta_i|x') = \overline{\theta}$, which would lead to $\overline{q}$. Formally, $(\underline{x}, \overline{x})$ fails the Intuitive Criterion if

$$\overline{x} \neq \arg\max_x \left(p(q_i - x) - (\overline{\theta} - x)^2 / 2 + \delta \overline{q} p^+\right) s.t. \tag{A.2}$$

$$p\left(q_i - \underline{x}\right) - \left(\underline{\theta} - \underline{x}\right)^2 / 2 + \delta \underline{q} p^+ > p(q_i - x) - \left(\underline{\theta} - x\right)^2 / 2 + \delta \overline{q} p^+.$$

[28] Formally, $\delta = \delta_a^T$ if δ_a is the annual discount factor. Substituting this, and the number of permits $q = \theta - v$ into (C) and (12) gives two equations (when the inequalities bind) for v as functions of T:

$$v_1 = (\overline{\theta} - \underline{\theta})^2 / 2\delta^T \Delta,$$
$$v_2 = z'^2 / \delta^T - z'(1-k)\sqrt{2\Delta} + (1-k)(\overline{\theta} - \underline{\theta}) \text{ where}$$
$$z' = (\overline{\theta} - \underline{\theta})\sqrt{2/\Delta} > z.$$

The inverse of these functions are drawn from the left to the right in the figure. Similar results can be derived assuming (S) and $s = s_a^T$.

[29] While the first welfare theorem states that the market equilibrium is first-best, the second states that any market equilibrium can be achieved by a proper reallocation of initial endowments. This is sometimes interpreted as suggesting that the combination of plan and markets can achieve remarkable outcomes, both in terms of efficiency and equality. This is not true when the plan is based on manipulable characteristics (see e.g. Roberts, 1984). If, in our model, the distributions of permits were based on the firms' past types (which are non-manipulable), there would be no distortions. However, the distributions are based on the expectation over types, and these are manipulable by the firms.

If Eq. (A.2) does not bind for $\overline{x}_n$,

$$\overline{x}_n \equiv \arg\max_x \left(p(q_i-x)-(\overline{\theta}-x)^2/2+\delta\overline{q}p^+\right)=\overline{\theta}-p,$$

$\overline{x}$ must equal $\overline{x}_n$. But if $\overline{x}_n$ does not satisfy Eq. (A.2), a separating $\overline{x}$ cannot pass the Intuitive Criterion unless Eq. (A.2) binds with equality, implying the emission level:

$$\overline{x}_b=\underline{\theta}-p+\sqrt{\left(\underline{\theta}-p\right)^2-\left(\left(\underline{\theta}-p\right)^2-2\delta\Delta p^+\right)}=\underline{\theta}-p+\sqrt{2\delta\Delta p^+}.$$

Clearly, $\overline{x}_b>\overline{x}_n$ if $\sqrt{2\delta\Delta p^+}>\overline{\theta}-\underline{\theta}$, and then $\overline{x}_n$ cannot satisfy Eq. (A.2). Hence, $\overline{x}=\max\{\overline{x}_n,\overline{x}_b\}$, giving Eq. (7).

(iii) Using Eqs. (6) and (7), $q=x=k\underline{x}+(1-k)\overline{x}=\theta-p+r \Rightarrow$ Eq. (8).

(i) From the proof of (ii), there is a unique separating equilibrium. Suppose there also were a pooling or a semi-pooling equilibrium where some firms of both types polluted x'. From Bayes' rule, $E(\theta_i|x')<\overline{\theta}$, and from (Q), their future quota would be $q'\equiv q+E\theta_i-\theta<\overline{q}$. Since $\overline{\theta}>\underline{\theta}$, it is always possible to find $x''>x'$ such that

$$p(q_i-x'')-\left(\underline{\theta}-x''\right)^2/2+\delta\overline{q}p^+<p(q_i-x')-\left(\underline{\theta}-x'\right)^2/2+\delta q'p^+ \tag{A.3}$$

$$p(q_i-x'')-(\overline{\theta}-x'')^2/2+\delta\overline{q}p^+>p(q_i-x')-(\overline{\theta}-x')^2/2+\delta q'p^+.$$

The first inequality implies that a deviation to x'' is never optimal for the low-cost type. (ii) The second inequality says that a deviation to q'' is optimal for the high-cost firm if the government concludes $E(\theta_i|x'')=\overline{\theta}$, such that its future quota is $\overline{q}$. Hence, the equilibrium fails the Intuitive Criterion.

Proof of Proposition 5. Since $E\theta_i=\theta$ for every i, w is maximized by setting $q_i=q\forall i$ and thereafter by maximizing u_i, which thus is the same for all is. Since the u_i^+s are independent of the q_is, we can simply maximize i's expected payoff in period 1,

$$\kappa-k\left(\underline{\theta}-\underline{x}\right)^2/2-(1-k)(\overline{\theta}-\overline{x})^2/2-vq.$$

From Eqs. (6)–(9), $\partial\underline{x}/\partial q=\partial\overline{x}/\partial q=-1$, and the first-order condition is:

$$k\left(\underline{\theta}-\underline{x}\right)+(1-k)(\overline{\theta}-\overline{x})-v=0\Rightarrow(10).$$

Proof of Proposition 6. In the first-best outcome,

$$\overline{\theta}-\overline{x}^*=\underline{\theta}-\underline{x}^*=\underline{\theta}-\frac{q-(1-k)\overline{x}^*}{k}\Rightarrow\overline{x}^*=q+k\left(\overline{\theta}-\underline{\theta}\right).$$

Since $\overline{x}^*>q_i=q$, high-cost firms *should* purchase permits. In equilibrium (from Eq. (7)):

$$\overline{x}=q+\overline{\theta}-\theta+rk/(1-k)=q+k\left(\overline{\theta}-\underline{\theta}\right)+rk/(1-k),$$

which is larger than $\overline{x}^*$ under (C). Thus, high-cost firms are purchasing more permits in equilibrium than what is socially optimal. Equivalently, low-cost firms sell more permits than what is optimal.

Proof of Proposition 7. Since q is the same under both regimes, we need only to compare firms' total (or expected) profit. Without trade, these are:

$$E\left(\kappa-(\theta_i-q)^2/2\right)=\kappa-E\theta_i^2/2+\theta q-q^2/2. \tag{A.4}$$

Suppose (C) holds. With trade, note that $\overline{x}-\underline{x}=\sqrt{2\delta p^+\Delta}$ and $x=q$ implies

$$\underline{x}=q-(1-k)\sqrt{2\delta p^+\Delta},\ \overline{x}=q+k\sqrt{2\delta p^+\Delta}.$$

Thus, summing the π_is gives:

$$\begin{aligned}&\kappa-k\left(\underline{\theta}-\underline{x}\right)^2/2-(1-k)(\overline{\theta}-\overline{x})^2/2\\&=\kappa-k\left(\underline{\theta}-q+(1-k)\sqrt{2\delta p^+\Delta}\right)^2/2-(1-k)\left(\overline{\theta}-q-k\sqrt{2\delta p^+\Delta}\right)^2/2\\&=\kappa-E\theta_i^2/2+\theta q-q^2/2+k(1-k)\sqrt{2\delta p^+\Delta}\left[\left(\overline{\theta}-\underline{\theta}\right)-\sqrt{\delta p^+\Delta/2}\right].\end{aligned} \tag{A.5}$$

Compared to Eq. (A.4), trade is good if and only if

$$k(1-k)\sqrt{2\delta p^+\Delta}\left(\overline{\theta}-\underline{\theta}\right)\geq k(1-k)\delta p^+\Delta\Rightarrow(12).$$

If (C) does not hold, trade is first best. Eq. (12) always holds in this case.

Proof of Proposition 9. Since q is constant over time, p follows from $p=\max\left\{\theta-q,\underline{\theta}-q+(1-k)\sqrt{2\delta\Delta p^+}\right\}$, which is an increasing function of p^+. To prevent p from exploding, $p=p^+$, and we should look for a fixed point in this equation. There are two possibilities. First, it may be that $p=\theta-q$ if $\theta-q\geq\underline{\theta}-q+(1-k)\sqrt{2\delta\Delta p^+}$. Then, $p^+=p=\theta-q$ implies:

$$\theta-q\geq\underline{\theta}-q+(1-k)\sqrt{2\delta\Delta(\theta-q)}\Rightarrow\sim(C).$$

Second, it may be that $\theta-q<\underline{\theta}-q+(1-k)\sqrt{2\delta\Delta p^+}$, such that p equals the latter. Solving for $\sqrt{p}=\sqrt{p^+}>0$ gives:

$$\sqrt{p}=(1-k)\sqrt{\delta\Delta/2}+\sqrt{(1-k)^2\delta\Delta/2+\underline{\theta}-q}. \tag{A.6}$$

Requiring $\theta-q<\underline{\theta}-q+(1-k)\sqrt{2\delta\Delta p^+}$ implies

$$\begin{aligned}&k\underline{\theta}+(1-k)\overline{\theta}-q<\\&\underline{\theta}-q+(1-k)\left[(1-k)\delta\Delta+\delta\Delta\sqrt{(1-k)^2+2\left(\underline{\theta}-q\right)/\delta\Delta}\right]\Rightarrow\\&\overline{\theta}-\underline{\theta}<(1-k)\delta\Delta+\delta\Delta\sqrt{(1-k)^2+2\left[\theta-q-(1-k)\left(\overline{\theta}-\underline{\theta}\right)\right]/\delta\Delta}\Rightarrow\\&\left[\overline{\theta}-\underline{\theta}-(1-k)\delta\Delta\right]^2<(1-k)^2(\delta\Delta)^2+2\left[\theta-q-(1-k)\left(\overline{\theta}-\underline{\theta}\right)\right]\delta\Delta\Rightarrow(C).\end{aligned}$$

Thus, (C) $\Leftrightarrow$ Eq. (A.6), while $p=\theta-q$ if (C) does not hold. Both equilibria (with and without $r>0$) cannot exist for the same parameter values. It just remains to calculate r under (C). From Eq. (A.6):

$$\begin{aligned}p&=(1-k)^2\delta\Delta/2+(1-k)\delta\Delta\sqrt{(1-k)^2+2\left(\underline{\theta}-q\right)/\delta\Delta}\\&\quad+\left[(1-k)^2\delta\Delta/2+\underline{\theta}-q\right]\\&=(1-k)^2\delta\Delta+\underline{\theta}-q+(1-k)\delta\Delta\sqrt{(1-k)^2+2\left(\underline{\theta}-q\right)/\delta\Delta}\\&=\theta-q+r,\text{where}\end{aligned}$$

$$r=(1-k)^2\delta\Delta-(1-k)\left(\overline{\theta}-\underline{\theta}\right)+(1-k)\delta\Delta\sqrt{(1-k)^2+2\left(\underline{\theta}-q\right)/\delta\Delta}\Rightarrow(13).$$

Proof of Proposition 10. When firms use Markov strategies, the q_is affect the firm strategies neither today, nor in the future. Thus, $\partial u_i/\partial q_i=p\forall i$, and utility is transferable. The government maximizes

$$\max_{\{q_i\}} w(u_1,u_2,\ldots)s.t.\int_I q_i di=q,$$

implying that every $(\partial w/\partial u_i)(\partial u_i/\partial q_i) = (\partial w/\partial u_i)p = \lambda$, if λ is the Lagrange multiplier. Thus, every u_i must be the same. Since $u_i = E\pi_i - vq + E\delta u_i^+$ and the government equalizes $E\delta u_i^+$ in the next period, it is enough to equalize the $E\pi_i$s this period. (i) If the government believes the firms are going to pollute optimally, as in Section 3.1, its problem is exactly as solved in the proof of Propositions 2 and 3, and so are the q_is and thus Δ. (ii) With rational expectations, the government uses Eqs. (6)–(7) and anticipates

$$E\left(\pi_i | \theta_i^- = \underline{\theta}\right) = (s + (1-s)k)\underline{\psi} + (1-s)(1-k)\overline{\psi} + pq_i,$$
$$E\left(\pi_j | \theta_j^- = \overline{\theta}\right) = (1-s)k\underline{\psi} + (1-(1-s)k)\overline{\psi} + pq_j, \text{ where}$$
$$\underline{\psi} \equiv \kappa - p^2/2 - p\left(\underline{\theta} - p\right) \text{ and}$$
$$\overline{\psi} \equiv \kappa - (\overline{\theta} - \overline{x})^2/2 - p\overline{x}$$
$$= \kappa - (p - r/(1-k))^2/2 - p(\overline{\theta} - p + r/(1-k))$$
$$= \kappa + p^2/2 - r^2/2(1-k)^2 - p\overline{\theta},$$

are the gross profits for low and high-cost firms, ignoring their revenues from selling their permits. Since

$$\underline{\psi} - \overline{\psi} = r^2/2(1-k)^2 + p\left(\overline{\theta} - \underline{\theta}\right),$$

$E(\pi_i|\theta_i^- = \underline{\theta}) = E(\pi_j|\theta_j^- = \overline{\theta})$ requires

$$p\left(q_j - q_i\right) = s\left(\underline{\psi} - \overline{\psi}\right) = s\left[r^2/2(1-k)^2 + p\left(\overline{\theta} - \underline{\theta}\right)\right],$$

which gives ($\tilde{S}$) since $\Delta = q_j - q_i$ when $E\theta_i^- = \underline{\theta}$ and $E\theta_j^- = \overline{\theta}$.

Proof of Proposition 11. Suppose, for a moment, there are a finite number of firms, n, and their representatives are bargaining at stage one in every period. The Nash bargaining solution is the argmax of the Nash Product,

$$\prod_I (u_i - \varsigma_i) \;\; s.t. \sum_I q_i/n = q, \text{ where}$$
$$u_i = E\pi_i - vq + E\delta u_i^+ \text{ and}$$
$$\varsigma_i \equiv \kappa - v\theta + E\delta u_i^+$$

is legislator i's default utility. Since the permit allocation makes utilities transferable, the equilibrium q_is make every u_i the same. Anticipating that this is true also in the future, $E\delta u_i^+$ is the same across the i's and, thus, every $E\pi_i$ must be the same. The allocation of the q_is is thus as in Sections 3 and 4. Given this, every legislator prefers to maximize the same u_i, and they agree on the (optimal) q and whether trade is good or not. Clearly, the argument also when $n \to \infty$.

Proof of Proposition 12. With probability $(1-\epsilon)$, firms trade and, then, $\int_I \pi_i di$ is independent of the q_is, for q given. Thus, when the government solves:

$$\max_{\{q_i\}_i} E\int_I \left[\epsilon\left(\kappa - (\theta_i - q_i)^2/2\right) + (1-\epsilon)\pi_i\right] di - vq \; s.t. \; q = \int_I q_i di,$$

the first-order condition is that every $\epsilon(\theta_i - q_i)$ must equal the Lagrange multiplier. This gives (Q) and thus (S).

Proof of Proposition 13. If the equilibrium is fully pooling, every firm pollutes the same, no information is revealed, and every initial quota is the same. The belief most likely to support this equilibrium is that any deviation is interpreted as a signal of low costs, and such a firm is, in the next period, allocated $q_i = \underline{q} = s\underline{\theta} + (1-s)\theta - v$ instead of $q = \theta - v$ which is optimal in the pooling equilibrium. If deviating, $x_i = \theta_i - p$ would be optimal. High-cost firms do not find a one-period deviation optimal if

$$\kappa - (\overline{\theta} - q)^2/2 + \delta p^+ s\left(\theta - \underline{\theta}\right) \geq \kappa - p^2/2 - p(\overline{\theta} - p - q) \Rightarrow$$
$$\delta p^+ s(1-k)\left(\overline{\theta} - \underline{\theta}\right) \geq p^2/2 - p(\overline{\theta} - q) + (\overline{\theta} - q)^2/2$$
$$= p^2/2 - p(\overline{\theta} - \theta + v) + (\overline{\theta} - \theta + v)^2/2$$
$$= (p-v)^2/2 - (p-v)k\left(\overline{\theta} - \underline{\theta}\right) + k^2\left(\overline{\theta} - \underline{\theta}\right)^2/2.$$

Similarly, low-cost firms do not find deviation attractive if

$$\kappa - \left(\underline{\theta} - q\right)^2/2 + \delta p^+ s\left(\theta - \underline{\theta}\right) \geq \kappa - p^2/2 - p\left(\underline{\theta} - p - q\right) \Rightarrow$$
$$\delta p^+ s(1-k)\left(\overline{\theta} - \underline{\theta}\right) \geq p^2/2 - p\left(\underline{\theta} - q\right) + \left(\underline{\theta} - q\right)^2/2$$
$$= p^2/2 - p\left(\underline{\theta} - \theta + v\right) + \left(\underline{\theta} - \theta + v\right)^2/2$$
$$= (p-v)^2/2 + (p-v)(1-k)\left(\overline{\theta} - \underline{\theta}\right) + (1-k)^2\left(\overline{\theta} - \underline{\theta}\right)^2/2.$$

Combined,

$$\delta p^+ s(1-k)\left(\overline{\theta} - \underline{\theta}\right) \geq (p-v)^2/2 - (p-v)k\left(\overline{\theta} - \underline{\theta}\right) + k^2\left(\overline{\theta} - \underline{\theta}\right)^2/2 + \max\left\{0, (p-v)\left(\overline{\theta} - \underline{\theta}\right) + (1-2k)\left(\overline{\theta} - \underline{\theta}\right)^2/2\right\}.$$

The p minimizing the right-hand side is $\underline{p} = v + (\overline{\theta} - \underline{\theta})(k - 1/2)$. This makes the right-hand side equal to $(\overline{\theta} - \underline{\theta})^2[(k - 1/2)^2/2 - k(k - 1/2) + k^2/2] = (\overline{\theta} - \underline{\theta})^2/8$. Substituting $p^+ = v$ for the second period concludes the proof.

Proof of Proposition 14. For low and high-cost firms, the first best requires $\underline{x}^* = \underline{\theta} - v$ and $\overline{x}^* = \overline{\theta} - v$, leading to the gross profits:

$$\underline{\psi}^* = \kappa - v^2/2 - p\left(\underline{\theta} - v\right)$$
$$\overline{\psi}^* = \kappa - v^2/2 - p(\overline{\theta} - v).$$

Maximizing w requires expected profits to be equalized. Thus, if i had proven to have high cost while j had proven to have low cost in the previous period, $q_i - q_j = s(\overline{\theta} - \underline{\theta})$ as in Section 3.1. The incentive constraint for the low-cost type is:

$$\underline{\psi}^* \geq \kappa - \left(\underline{\theta} - \overline{\theta} + v\right)^2/2 - p(\overline{\theta} - v) + \delta p^+ \Delta \Rightarrow$$
$$p - \delta s p^+ \geq v - \left(\overline{\theta} - \underline{\theta}\right)/2.$$

The incentive constraint for the high-cost type is

$$\overline{\psi}^* + \delta p^+ \Delta \geq \kappa - \left(\overline{\theta} - \underline{\theta} + v\right)^2/2 - p\left(\underline{\theta} - v\right) \Rightarrow$$
$$p - \delta s p^+ \leq v + \left(\overline{\theta} - \underline{\theta}\right)/2.$$

Setting $p = p^+$ and requiring both incentive constraints to hold concludes the proof.

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