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Abstract

This paper investigates the sequential announcement of domestic emissions caps by regulators in a federal or international-based tradable pollution permit market for a transboundary pollutant. A leader-follower framework is used to analyse the consequences of regulators sequentially announcing domestic allocation caps. We find the sequential choice of domestic allocation caps is sub-optimal and depends on the follower's reaction to the leader's choice. Furthermore, the marginal damage and the degree to which allocations are substitutes or complements affects whether the leader changes from being a net permit buyer (seller) of permits to a seller (buyer).

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1 Introduction

The fundamental idea behind tradable pollution permit markets allows one regulator the ability to create and allocate pollution rights to firms. Due to the competitive trading of permits in the market, the pollutant can normally be controlled efficiently—where abatement efforts are efficiently distributed among firms (Coase 1960; Montgomery 1972). In contrast to this simple theory, many current tradable permit markets span many regulatory bodies, such as schemes that control pollution over multiple states or countries (see, for example, Ellerman et al. 2000; Ellerman et al. 2007). Due to this phenomenon, an active debate has begun to focus on the strategic issues that arise when tradable permit markets are controlled by multiple regulators. As Helm (2003) has shown, allowing multiple regulators to simultaneously determine a proportion of the aggregate emissions cap results in strategic behaviour that can increase aggregate emissions above the socially optimal level of emissions. Yet, the timing of regulators' allocation choices has often been ignored. In particular, there has been no discussion on the consequences of allowing regulators to sequentially announce emissions caps. Therefore, it is the aim of this paper to consider regulators' optimal behaviour and the social optimality of a tradable permit market when multiple regulators are allowed to sequentially announce their own (domestic) emissions caps.

In this paper, we investigate the affects on a federal or international-based tradable pollution permit market when the level of permit allocation is determined by multiple regulators. The model is split into two stages: In the first stage, two regulators *sequentially* announce a level of pollution permits (domestic emissions cap) for firms under their jurisdiction (i.e. in their geographical area). In the second stage, all firms obtain a permit allocation (determined in stage one) and decide on a level of emissions to pollute in the perfectly competitive tradable permit market. We find that the sequential determination of regional emissions caps are socially suboptimal. When the follower's choice of emissions cap is complementary ("weakly" substitutable) the equilibrium level of aggregate allocation is closer too (further from) the socially optimal level. If the choice of emissions cap is "strongly" substitutable the equilibrium level of aggregate allocation is smaller than the socially optimal level. Furthermore, the extent to which the follower's allocation choice changes affects whether the leader is a net buyer or seller of permits. Our model is also reduced to consider a special case, where both regulators simultaneously announce their emissions caps.

In existing tradable permit markets, it is increasingly common for multiple regulators to participate in the development of market trading rules, allocation selection and monitoring of participating firms. For example, the U.S. "Acid Rain" program consists of numerous state regulators within a federal-based tradable permit market. It is possible that such a design may lead to state-level regulators behaving strategically (such as the strategic use of penalties and enforcement rules) in order to maximise their welfare (Santore et al. 2001). It is also a common occurrence in the "new wave" of tradable permit markets, such as the Regional Greenhouse Gas Initiative (RGGI) and the European Union Emissions Trading Scheme (EU-ETS) that aim to control CO_2 emissions in ten Northeastern US states and 27 EU Member States, respectively (Burtraw et al. 2005; Ellerman et al. 2007). The clearest example of strategic interaction exists between Member State regulators (governments) in the EU-ETS. Each Member State, through submission of their National Allocation Plan (NAP), has, among others things, the right to determine the composition and level of their allowance allocation–albeit with the approval of the European Commission (Ellerman et al. 2007).

The theoretical discussions of strategic behaviour in environmental policy have been extensively investigated (see, for example, Barrett 1994; Silva and Caplan 1997; Ulph 1996; 2000; Santore et al. 2001). A large part of the literature discusses the incentives for governments to act strategically in product markets with transboundary pollution (see Barrett (1994) for an overview). Another aspect of the literature, and closer in topic to this paper, focuses on the strategic action of federal states (or governments). Silva and Caplan (1997) investigate the effectiveness of federal environmental policy in which regional and central governments were modelled to be both leaders and followers and find when the central government lead environmental policy, transboundary pollution is larger than the socially optimal level. However, when the regional government is selected as the leader and the central government provides incentives for efficient decentralised behaviour, it is shown to be socially optimal. Very few studies have attempted to investigate strategic environmental policy in tradable permit markets. Santore et al. (2001) examine a federal-based model to investigate the incentives for US states to affect the SO_2 market and show that states do have an incentive to intervene in the SO_2 permit market (through pollution penalties) and the outcome, in general, is Pareto inefficient.

Two studies closest to our argument are Helm (2003) and D'Amato and Valentini (2006). Helm (2003) considers an international tradable permit market with n non-cooperative countries and uses a two stage game where in the first stage, each country simultaneously selects a level of emissions for its representative firm. Then, in stage two, the firm from each country takes the governments allocation as given and selects a level of emissions to pollute. Helm (2003) finds, that the introduction of trading actually increases the level of aggregate emissions where "more environmental concerned" countries choose less permits but this is offset by the selection of more permits from the "less environmentally concerned" countries. However, Helm's (2003) study is restricted to only simultaneous moves between governments. We use a similar framework to Helm (2003) in that we have a two stage game but allow for the possibility of sequential announcements. D'Amato and Valentini (2006) extend the results of Helm (2003) by including a perfectly competitive product market and provide theoretical evidence for "excessive" allocation choices in the European Emissions Trading Scheme and are able to obtain the social optimality of a simultaneous-moves game with two regulators. However, our focus is on the social optimality of sequentially allocating domestic caps in an international or federal tradable permit market. Our paper is sufficiently general to allow the findings of Helm (2003) and D'Amato and Valentini (2006) to appear as special cases of our model.

Both studies give rigorous accounts of the incentives associated with multiple regulators (governments) simultaneously selecting domestic allocation caps but ignore the consequences of sequential selection. The interactions described by Helm (2003) and D'Amato and Valentini (2006) would be better placed in a more realistic context which could investigate regulators (or governments) sequentially setting domestic allocation caps. Indeed, the sequential announcement of domestic permit caps has already occurred in the EU-ETS. Before the implementation of phase I (2005-2007), Member States had to notify the European Commission of their NAP by the 1st May 2004, yet as Zapfel (2007, p 23) explains:

> "[O]nly seven Member States...notified a plan close to the official date. On 7 July 2004, the date of the adoption of the Commission decisions on the first plans, nine plans were still outstanding. The last plan was received by the Commission on 3 January 2005, i.e. some nine months after the due date"

With the sequential announcement of NAPs occurring, it has been suggested by Harrison and Radov (2007, pp 41-61) that the first published draft NAP, announced by the UK, was "one of the most influential of the twenty-five Member State plans developed to implement the EU-ETS" as it was "viewed by some commentators as an attempt to influence the development of NAPs in other Member States". Furthermore, it was apparent that "[s]ome member states may in fact have delayed notification of plans...not merely for technical reasons, but also to see what standard the Commission would apply" (Zapfel 2007, p25).

Such anecdotal evidence of sequential allocation announcements suggests that strategic behaviour may play a role in Member States' choice of permit allocations.

If so, it is important to consider whether the sequential announcement of domestic emission caps (and the additional information obtained) has any consequence for optimal allocation setting and social optimality. While our analysis is motivated by the EU-ETS, our model is sufficiently general to discuss federal or other international-based tradable permit markets.

A unique aspect of our model is the sequential announcement of regulators' domestic emissions caps. The above literature on international and federal-based tradable permit markets ignores the possibility that regulators may be able to announce their choice of domestic emissions caps at different time periods. Bárcena-Ruiz (2006) investigates whether governments prefer to be leaders or followers when implementing pollution taxes and finds the degree to which they prefer to lead depends on the extent to which the pollution "spills over" to the other government. However, unlike our paper, Bárcena-Ruiz (2006) does not consider a tradable permit market.

In our simple sequential model, we allow one regulator to announce their domestic allocation cap first, that is, become the leader. Then, after observing this action, the remaining regulator (the follower) decides on an appropriate domestic allocation cap. After both regulators have decided on a domestic allocation cap, the permits are then *simultaneously* distributed to participating firms in the tradable permit market. We find the sequential announcement of permits is socially sub-optimal. Aggregate emissions are chosen further from (closer too) the socially optimal level compared to the simultaneous case when the follower's domestic allocation cap is "weakly" substitutable (complementary). In certain circumstances it is possible for the leader to change from a net supplier (buyer) of permits to a net buyer (supplier).

The paper is organised as follows: In Section 2 the basic model and the socially optimal case are discussed. In Section 3 the sequential announcement of permit allocations is discussed. We then illustrate the special case of simultaneous allocation setting. In Section 4 the simultaneous and sequential allocations are compared and finally Section 5 has some concluding remarks.

2 The Basic Model

Consider a tradable permit market for a transboundary pollutant where there are two distinct regulators (or governments) $k = i, j$.[1] Each regulator has, under their jurisdiction, one representative polluting firm in their geographical region, which we denote as firm $k = i, j$. It is the responsibility of both regulators to select a domestic emissions cap that is allocated to their representative firm.[2] The aggregation of the two domestic emissions caps determines the aggregate supply of permits in the perfectly competitive permit market. Furthermore, both firms can freely trade permits between the two regions.

Our model is similar in framework to Helm (2003) where the game is split into two stages. In stage one, regulators sequentially announce a domestic emissions cap $a_k \in \mathbb{R}_+$ for $k = i, j$, to be allocated to their representative firm in order to maximise welfare in their jurisdiction. Without loss of generality, we assume that regulator i announces an emissions cap first (the leader). Regulator j (the follower), observes regulator i's decision, and using this information, announces an emissions cap.

In stage two, the domestic emissions caps from stage one are *simultaneously* distributed to firms participating in the perfectly competitive tradable permit market. Firms take the initial allocation as given and select a level of emissions to pollute $e_k \in \mathbb{R}_+$ for $k = i, j$. To coincide with permit allocation procedures in many existing tradable permit markets, such as the EU-ETS, we ignore the possibility that participating firms in the market obtain permits at different time periods. Instead, all regulators distribute their chosen permit allocation to firms at one designated time period.

In order to find the subgame Nash equilibrium of this game, we use backward

[1] In this paper, the use of the term "regulator" and "government" are interchangeable as their main task—the announcement of domestic emissions caps—is identical. For tractable simplicity, we assume throughout that no other regulatory influence exists other than the two regulators involved in announcing domestic emissions caps.

[2] We assume throughout that the tradable permit market rules, such as rules on enforcement and monitoring, have been unanimously agreed by the regulators before the market is operational.

induction by first solving the optimal strategy of each firm (stage two) and then the regulators' optimal choice of permit allocation (stage one).

2.1 Stage Two: Firms' Emissions Choices

In stage two, the perfectly competitive tradable permit market commences with the distribution of domestic emissions caps to participating firms (which was determined by regulators in stage one). In the tradable permit market, firm $k = i, j$ takes the equilibrium permit market price p^* and the allocation from its respective regulator a_k, as given. Firm k selects a level of emissions e_k for $k = i, j$ to maximise (minimise) profit (cost) from the tradable permit market where the cost of abatement for firm k is given by $c_k(e_k)$ where $\frac{\partial c_k(e_k)}{\partial e_k} < 0$, $\frac{\partial^2 c_k(e_k)}{\partial e_k^2} > 0$ for $k = i,\ j$. Formally, firm k's objective function is:

$$\max_{e_k} \quad p^*(a_k - e_k) - c_k(e_k) \qquad \text{for } k = i, j \tag{1}$$

Equation (1) shows firms' payoff from the permit market consisting of the revenue (cost) created by selling (buying) permits and the cost of abatement. Differentiating equation (1) with respect to e_k gives the first order condition for firm k:

$$-\frac{\partial c_k(e_k)}{\partial e_k} - p^* = 0 \qquad \text{for } k = i, j \tag{2}$$

and the equilibrium market clearing condition is:

$$e_i^*(p^*) + e_j^*(p^*) = a_i + a_j \equiv a \tag{3}$$

where e_k^* is the equilibrium level of emissions for firm $k = i, j$ and a is the total permit supply across both regions. Equation (2) is the standard result of a perfectly competitive tradable permit market. Both firms choose a level of emissions so that their marginal abatement cost is equated to the market equilibrium permit price and as a consequence abatement effort is efficiently distributed between firms. Equation

(3) is the equilibrium market clearing condition where the total amount of pollution emitted equals the aggregate supply of permits in the tradable permit market. To determine the responsiveness of the equilibrium permit price to aggregate allocation, we differentiate (2) with respect p^*:

$$-\frac{\partial^2 c_k(e_k)}{\partial e_k^2}\frac{\partial e_k}{\partial p^*} - 1 = 0 \qquad \text{for } k = i, j \tag{4}$$

and differentiate (3) with respect to a_k :

$$\left(\frac{\partial e_i}{\partial p^*} + \frac{\partial e_j}{\partial p^*}\right)\frac{\partial p^*}{\partial a} = 1 \qquad \text{for } k = i, j \tag{5}$$

By substituting (4) into (5) we obtain:

$$\frac{\partial p^*}{\partial a} = -\left(\frac{1}{\frac{1}{\frac{\partial^2 c_i(e_i)}{\partial e_i^2}} + \frac{1}{\frac{\partial^2 c_j(e_j)}{\partial e_j^2}}}\right) < 0 \tag{6}$$

From equation (6), and the assumptions about the second derivative of the pollution abatement cost function, it is clear that as the level of aggregate emissions cap a increases, the permit price decreases. We now consider the optimal behaviour of regulators in stage one.

2.2 Stage One: Regulators' Choice of Domestic Emissions Cap

In stage one, regulators sequentially announce a domestic emissions cap for their representative firm in order to maximise social welfare in their region.[3] Regulators have perfect knowledge of their firm's reaction in stage two. In particular, regulators understand that the equilibrium permit price and the level of emissions chosen by firms are dependent on the aggregate level of permits in the market, that is $p^* =$

[3] It is assumed throughout that regulators' announcement of domestic emissions caps are credible and involve full commitment.

$p^*(a)$ and $e_k^* = e_k^*(a)$ for $k = i, j$ where a is the regulators' aggregate supply of permits to the market ($a \equiv a_i + a_j$).

The welfare of regulator k consists of net profit from its polluting firm minus the damage associated with the total level of emissions in its jurisdiction. We assume the pollutant is transboundary so that pollution from both firms cause damages to both regulators. Damage is represented by $D_k(e_i + e_j)$ where $\frac{\partial D_k(e_i+e_j)}{\partial e_k}, \frac{\partial^2 D_k(e_i+e_j)}{\partial e_k^2} > 0$ for $k = i, j$. In equilibrium, as the aggregate level of emissions must equal the aggregate permit allocation, it follows from (3) that $D_k(e_i + e_j) = D_k(a_i + a_j) = D_k(a)$. Henceforth, we represent regulator k's damage function by $D_k(a)$. We allow the damage experienced by both regulators to be asymmetric in that $D_i(a) \neq D_j(a)$.

Formally, the objective function of regulator k is:

$$\max_{a_k} W_k = p^*(a)(a_k - e_k^*(a)) - c_k(e_k^*(a)) - D_k(a) \qquad \text{for } k = i, j \tag{7}$$

where e_i^*, p^* are the equilibrium level of emissions and permit price determined by equations (2) and (3), respectively.

In the sequential announcement game, regulator i moves first (the leader) by announcing a level of permit allocation. Given this information, regulator j (the follower) selects a level of permit allocation. The sequence of play is common knowledge to both regulators. It follows, then, that the difference in regulators' objective functions occurs as a result of the timing of decisions.

Regulator j, the follower, takes as given, the leader's choice of allocation. Therefore, regulator j assumes the aggregate emissions cap a is:

$$a_i + a_j \tag{8}$$

Using backward induction, regulator i, the leader, has perfect knowledge of the reaction of regulator j and understands its choice of allocation will alter the total allocation of permits, both directly (through its own choice of allocation) and indirectly (through regulator j's reaction to the leader's choice of allocation). As a consequence, the *leader* understands that the total allocation in the market is:

$$a_i + a_j(a_i) \tag{9}$$

We show later in this paper that a special case of the model allows a game where both regulators announce allocations simultaneously, that is, both regulators are Cournot followers.

2.3 Socially Optimal Level of Allocation

To aid comparisons throughout the paper, we identify the socially optimal outcome for a centralised planner.

The centralised planner aims to simultaneously choose a domestic emissions cap for both regions. The social planner's objective function is to maximise the sum of regulators' welfare functions:

$$\max_{a_i, a_j} \quad W_i + W_j \tag{10}$$

which, given (7) and (8), is:

$$\max_{a_i, a_j} p^*(a)(a_i - e_i^*(a)) - c_i(e_i^*(a)) - D_i(a) + p^*(a)(a_j - e_j^*(a)) - c_j(e_j^*(a)) - D_j(a) \tag{11}$$

Differentiating equation (11) with respect to a_i and a_j respectively, gives:

$$\begin{aligned} & p'^*(a) \cdot (a_i - e_i^*(a)) + p^*(a)(1 - e_i^{*\prime}(a)) + p'^*(a) \cdot (a_j - e_j^*(a)) \\ & -p^*(a) e_j^{*\prime}(a) - c_i'(e_i^*(a)) - c_j'(e_j^*(a)) - \frac{\partial D_i}{\partial a}\frac{\partial a}{\partial a_i} - \frac{\partial D_j}{\partial a}\frac{\partial a}{\partial a_i} \end{aligned} \tag{12}$$

and

$$p'^{*}(a)\cdot(a_j-e_j^{*}(a))+p^{*}(a)(1-e_j^{*\prime}(a))+p'^{*}(a)\cdot(a_i-e_i^{*}(a)) \tag{13}$$
$$-p^{*}(a)e_i^{*\prime}(a)-c_j'(e_j^{*}(a))-c_i'(e_i^{*}(a))-\frac{\partial D_i}{\partial a}\frac{\partial a}{\partial a_j}-\frac{\partial D_j}{\partial a}\frac{\partial a}{\partial a_j}$$

where $c_i'(e_i^{*}(a))=\frac{\partial c_i}{\partial ei}\frac{\partial e_i}{\partial p^{*}}\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}$, $c_j'(e_j^{*}(a))=\frac{\partial c_j}{\partial ej}\frac{\partial e_j}{\partial p^{*}}\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}$, $e_i^{*\prime}(a)=\frac{\partial e_i}{\partial p^{*}}\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}$, $e_j^{*\prime}(a)=\frac{\partial e_j}{\partial p^{*}}\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}$, $p'^{*}(a)=\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}$ and $\frac{\partial a}{\partial a_k}=1$ for $k=i,j$. Equations (12) and (13) can be simplified by noting that, in equilibrium, the market clears so that $(a_i-e_i^{*}(a))+(a_j-e_j^{*}(a))=0$. Also, from equation (2) we know that each firm will choose a level of emissions to equate their marginal abatement cost with the permit price, it follows that $-\frac{\partial c_i}{\partial ei}\frac{\partial e_i}{\partial p^{*}}\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}=p^{*}\frac{\partial e_i}{\partial p^{*}}\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}$ and $-\frac{\partial c_j}{\partial ej}\frac{\partial e_j}{\partial p^{*}}\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}=p^{*}\frac{\partial e_j}{\partial p^{*}}\frac{\partial p^{*}}{\partial a}\frac{\partial a}{\partial a_k}$ for $k=i,j$. Therefore equating (12) and (13) to zero for the optimum and simplifying, we obtain:[4]

$$p^{*}-\frac{\partial D_i}{\partial a}\frac{\partial a}{\partial a_i}-\frac{\partial D_j}{\partial a}\frac{\partial a}{\partial a_i}=0 \tag{14}$$
$$p^{*}-\frac{\partial D_i}{\partial a}\frac{\partial a}{\partial a_j}-\frac{\partial D_j}{\partial a}\frac{\partial a}{\partial a_j}=0 \tag{15}$$

From equations (14) and (15), it is clear that for social optimality to occur, regulator k's domestic emissions cap must be chosen so that the cost of emissions (the permit price) is equal to the sum of regulators' marginal damages. In other words, each regulator considers the marginal damage on *both* regulators when selecting a domestic emissions cap.

To investigate aggregate emissions, we sum (14) and (15) together and rearrange:

$$2p^{*}=\frac{\partial D_i}{\partial a}\left(\frac{\partial a}{\partial a_i}+\frac{\partial a}{\partial a_j}\right)+\frac{\partial D_j}{\partial a}\left(\frac{\partial a}{\partial a_i}+\frac{\partial a}{\partial a_j}\right) \tag{16}$$

[4]Given the assumptions about the damage functions and the result from equation (6), it is clear that the second order conditions hold for optimality.

Equation (16) shows, for the market, that at the socially optimal level of aggregate allocation, the aggregate marginal benefit of allocation (the permit price) equals the sum of regulators' aggregate marginal damages of allocation (that is, each regulators marginal damage caused by *both* a_i and a_j).[5] As the central planner selects a_i and a_j simultaneously, the aggregate emissions cap is $a = a_i + a_j$ and it follows that $\frac{\partial a}{\partial a_k} = 1$ for $k = i, j$. For ease of comparison throughout the paper, equation (16) can be further simplified to:

$$p^* = \frac{\partial D_i}{\partial a} + \frac{\partial D_j}{\partial a} \tag{17}$$

Equation (17) shows that, for the market as a whole, the social optimum level of aggregate emissions occurs when the *aggregate* emissions cap is chosen so that the sum of regulators' aggregate marginal damages (for the aggregate emissions cap) equals the permit price.

We proceed by investigating the affects of the sequential announcement of permit allocations by regulators.

3 Sequential Announcement of Permit Allocations

In this section we start by examining the optimal allocation choice of the follower and, given this, work out the optimal strategy for the leader.

The follower, regulator j, takes the other regulator's domestic cap a_i as given. Therefore, substituting equation (8) into (7) and differentiating with respect to a_j gives regulator j's reaction function:

$$\frac{\partial p^*}{\partial a} \cdot (a_j - e_j^*(a)) + p^* - \frac{\partial D_j(a)}{\partial a} = 0 \tag{18}$$

where $p^* = -\frac{\partial c_k(e_k)}{\partial e_k}$ for $k = i, j$, from (2). The follower will choose an opti-

[5] The aggregate marginal benefit of allocation can also be considered as the sum of firms' marginal abatement costs.

mal level of allocation a_j^* so that (18) holds. Next, we solve the leader's problem. Regulator i, the leader, understands that the follower will react to its allocation announcement. Substituting equation (9) into (7) and differentiating with respect to a_i gives:

$$\frac{\partial p^*}{\partial a} \cdot (a_i - e_i^*(a)) \left(1 + \frac{\partial a_j}{\partial a_i}\right) + p^* \left(1 - \frac{\partial e}{\partial p^*} \frac{\partial p^*}{\partial a} \left(1 + \frac{\partial a_j}{\partial a_i}\right)\right) \tag{19}$$
$$- \frac{\partial c}{\partial e^*} \frac{\partial e}{\partial p^*} \frac{\partial p^*}{\partial a} \left(1 + \frac{\partial a_j}{\partial a_i}\right) - \frac{\partial D_i(a)}{\partial a} \left(1 + \frac{\partial a_j}{\partial a_i}\right)$$

Noting equation (2), it follows that $-p^* \frac{\partial e}{\partial p^*} \frac{\partial p^*}{\partial a} \left(1 + \frac{\partial a_j}{\partial a_i}\right) - \frac{\partial c}{\partial e^*} \frac{\partial e}{\partial p^*} \frac{\partial p^*}{\partial a} \left(1 + \frac{\partial a_j}{\partial a_i}\right) = 0$. Therefore, at the optimum, equation (19) can be reduced to:

$$\frac{\partial p^*}{\partial a} \cdot (a_i - e_i^*(a)) \left(1 + \frac{\partial a_j}{\partial a_i}\right) + p^* - \frac{\partial D_i(a)}{\partial a} \left(1 + \frac{\partial a_j}{\partial a_i}\right) = 0 \tag{20}$$

Assuming that $\phi \equiv \left[1 + \frac{\partial a_j}{\partial a_i}\right]$, this can be easily expressed as:[6]

$$\frac{\partial p^*}{\partial a} \cdot (a_i - e_i^*(a)) + \frac{p^*}{\phi} - \frac{\partial D_i(a)}{\partial a} = 0 \tag{21}$$

The leader will choose an optimal level of allocation a_i^* so that (21) holds. Comparing (18) and (21), both reaction functions are similar in that three influences affect the choice of allocation (Helm 2003). Increasing allocation increases regulators' marginal damages. Second, each regulator benefits from the additional payoff it receives from increasing allocation, that is, the regulator obtains the value of the permit price for each new permit chosen (p^*) by either selling the additional unit or reducing the amount demanded by the additional unit. Lastly, increasing the permit allocation

[6] The second order conditions for the solution hold for the follower when: $\frac{\partial^2 p^*}{\partial a^2} \cdot (a_j - e_j^*(a)) - \frac{\partial^2 c_j(e_j)}{\partial e_j^2} \left(\frac{\partial e_j^*}{\partial p^*} \cdot \frac{\partial p^*}{\partial a}\right)^2 - \frac{\partial^2 D_j(a)}{\partial a^2} < 0$ and for the leader when: $(a_i - e_i^*(a)) \left[\frac{\partial^2 p^*}{\partial a^2} \cdot \left(\frac{\partial a}{\partial a_i}\right)^2 + \frac{\partial p^*}{\partial a} \frac{\partial^2 a}{\partial a_i^2}\right] + 2 \frac{\partial p^*}{\partial a} \frac{\partial a}{\partial a_i} - \frac{\partial e_i^*}{\partial p^*} \left[\frac{\partial p^*}{\partial a} \cdot \frac{\partial a}{\partial a_i}\right]^2 - \frac{\partial^2 D_i(a)}{\partial a^2} \cdot \left(\frac{\partial a}{\partial a_i}\right)^2 - \frac{\partial D_i(a)}{\partial a} \frac{\partial^2 a}{\partial a_i^2} < 0$. In general terms, optimality occurs when $\frac{\partial^2 p^*}{\partial a^2}$, $\frac{\partial^2 a}{\partial a_i^2}$ are relatively small and $\frac{\partial^2 c(e_k)}{\partial e_k^2}$ is relatively large. In the following we assume that the optimality of the second order conditions holds.

will increase the aggregate supply of permits. Therefore, an increase in allocation will reduce the permit price received for each additional permit bought or sold by $\frac{\partial p^*}{\partial a}$, which from (6), is negative.

The main difference between the two reaction functions arises as the leader has additional information about the reaction of the follower (ϕ). From (21), it is clear that ϕ, the *conjectural derivative*, will alter the leader's choice of allocation compared to that of the follower (Friedman 1983). Summing equations (18) and (21) together and rearranging, we obtain one of our main results:

Proposition 1 *When regulators sequentially determine their domestic emissions caps then the aggregate emissions cap in the market equilibrium occurs when:*

$$p^* = \frac{\phi}{1+\phi}\left[\frac{\partial D_i(a)}{\partial a} + \frac{\partial D_j(a)}{\partial a}\right] \tag{22}$$

where $\phi = \left[1 + \frac{\partial a_j}{\partial a_i}\right]$, *regulator* i *(the leader) chooses a domestic cap from (21) and regulator* j *(the follower) chooses a domestic cap from (18).*

Proposition 1 presents an expression which relates regulators' aggregate marginal damages with the permit price (given an aggregate emissions cap). From equation (22) it is immediate that $\frac{\phi}{1+\phi} \neq 1$, $\forall\ \phi$. It follows by comparing (17) and (22) that the aggregate emissions in the market equilibrium will never reach the socially optimal level of aggregate emissions. Both regulators do not take into consideration the affect of their permit allocation on the other regulator's damage function and, as the result, aggregate emissions are larger than the socially optimal level. We return to this in the following section.

As with any Stackelberg (leader-follower) model, the leader's knowledge of whether the follower selects allocation as a substitute or complement is crucial to the level of allocation chosen. When $\phi < 1$, the follower's allocation choice is negatively related to the choice made by the leader—the follower's choice of domestic allocation is a substitute. We denote two types of substitute: "weak" and "strong" substitutes.

For "weak" substitutes the follower's response is relatively insensitive ($\phi \in (0, 1)$) and for "strong" substitutes the reaction is relatively sensitive ($\phi \in (-\infty, -1)$). Further, when $\phi > 1$, the follower's choice of allocation is a complement (i.e. the follower increases allocation when the leader increases allocation).

To what extent the choice of allocations are substitutes or complements depends on the functional forms placed on firms' abatement costs and regulators' damage functions. Bárcena-Ruiz (2006) and Kennedy (1994) have shown that, for the case of environmental taxes, the selection of substitutes or complements depends on the extent to which pollution "spillovers" to the other regulator, that is, to what extent the pollutant is transboundary. A similar logic applies here: parameters in the functional form of the abatement cost and damage functions will determine the characteristics of allocation choice. However, we abstract from the causes of what determines allocation choices to be substitutes or complements, and instead focus on the optimal behaviour and social optimality of the permit market when the characteristics of allocation choices have been ex-ante determined. From equation (22), it is immediate that a special case exists when $\phi = 1$.

3.1 Special Case: Cournot-Nash Game $\phi = 1$

Assume that $\phi \equiv \left[1 + \frac{\partial a_j}{\partial a_i}\right] = 1$, where the conjectural derivative is zero, $\frac{\partial a_j}{\partial a_i} = 0$. In this game, the leader takes as given, the follower's level of allocation. This means that both regulators simultaneously announce allocations given the others' choice of allocation so that both are followers—a Cournot-Nash game. This can be seen more clearly by substituting $\phi = 1$ into equations (21) and (22) and summing so that:

Corollary 2 *When $\phi = 1$, regulators $k = i, j$ simultaneously announce permit allocations so that their reaction functions are*

$$\frac{\partial p^*}{\partial a} \cdot (a_k - e_k^*(a)) + p^* - \frac{\partial D_k(a)}{\partial a} = 0 \tag{23}$$

and the aggregate emissions cap, at the market equilibrium, occurs when

$$p^* = \frac{1}{2}\left[\frac{\partial D_i(a)}{\partial a} + \frac{\partial D_j(a)}{\partial a}\right] \tag{24}$$

for $k = i, j$.

This is in line with Helm (2003) and D'Amato and Valentini (2006). Comparing equation (17) with (24) shows that when domestic caps are chosen simultaneously, the socially optimal level of allocation (emissions) is not achieved. It follows that decentralising the allocation process to separate regulators actually increases the aggregate level of emissions relative to the socially optimal level of emissions. Similar to the sequential game, this occurs as regulator k does not take into consideration the affect of it's emissions on the other regulator's damage function.

4 Sequential vs. Simultaneous Announcement of Permit Allocations

In this section, we directly compare the social optimality of simultaneously and sequentially announcing domestic emissions caps. Furthermore, we show that allowing the sequential announcements of domestic emissions caps can significantly alter whether the leader decides to be a permit buyer or seller.

Comparing the socially optimal level of allocation (17) with the levels for the simultaneous (22) and sequential (24) games, shows that as $\frac{\phi}{1+\phi} \neq 1 \ \forall \ \phi$, allowing regulators the option to determine their own domestic permit cap, either sequentially or simultaneously, is socially sub-optimal.

This can be seen clearly by mapping $\frac{\phi}{1+\phi}$ for all possible combinations of $\frac{\partial a_j}{\partial a_i}$.[7] Figure 1 shows the values of the asymptotic hyperbola $\frac{\phi}{1+\phi}$ when the reaction of the follower changes (i.e. $\frac{\partial a_j}{\partial a_i}$ changes). From Figure 1, the socially optimal allocation

[7] We exclude $\frac{\partial a_j}{\partial a_i} \in [-2, -1]$ due to the asymptotic behaviour of $\frac{\phi}{1+\phi}$.

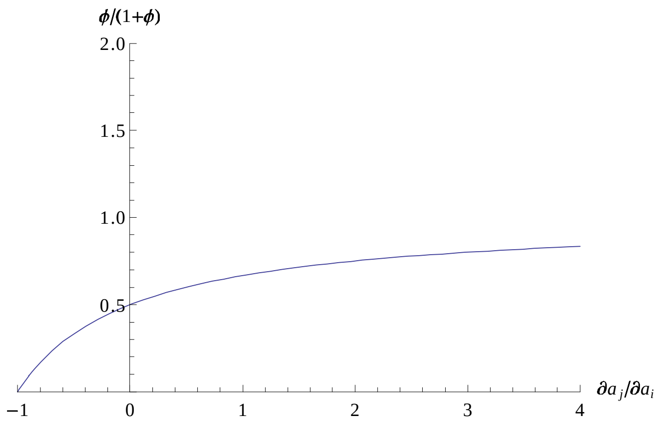

Figure 1: Social optimality when $\phi > 0$

occurs when $\frac{\phi}{1+\phi} = 1$ and due to the assumption that $\frac{\partial D_k(e_i+e_j)}{\partial e_k} > 0$ for $k = i, j$, values of $\frac{\phi}{1+\phi}$ less than 1 represent a larger allocation than the socially optimal level. Further, as shown above, the simultaneous announcement of allocations, $\frac{\partial a_j}{\partial a_i} = 0$, is $\frac{\phi}{1+\phi} = \frac{1}{2}$.

First, consider the case of complementarily allocation choice $\frac{\partial a_j}{\partial a_i} > 0$. As can be seen from Figure 1, if complementarily exists, the sequential cap will be larger than the socially optimal level but smaller than the cap chosen in the simultaneous game. As $\frac{\partial a_j}{\partial a_i} \to \infty$, one observes an aggregate emissions cap converging to the socially optimal level. Given the leader understands the follower acts in a complementarily fashion, any increase in the leader's allocation will result in an increase in allocation from the follower which will further depreciate the permit price. Therefore, the leader may consider reducing allocation in order to prevent a dramatic fall in the equilibrium permit price. The degree to which this happens depends on the sensitivity of both the price change (given by (6)) and the follower's reaction. Second, assume the follower announces allocation as a "weak" substitute $\frac{\partial a_j}{\partial a_i} \in (-1, 0)$. From Figure 1, it can be seen that the aggregate allocation is larger than the socially optimal level and the simultaneous game. Intuitively, the follower's reaction does not outweigh an increase in the leader's allocation and, as a consequence, aggregate emissions increase. Again, the degree to which aggregate allocation changes

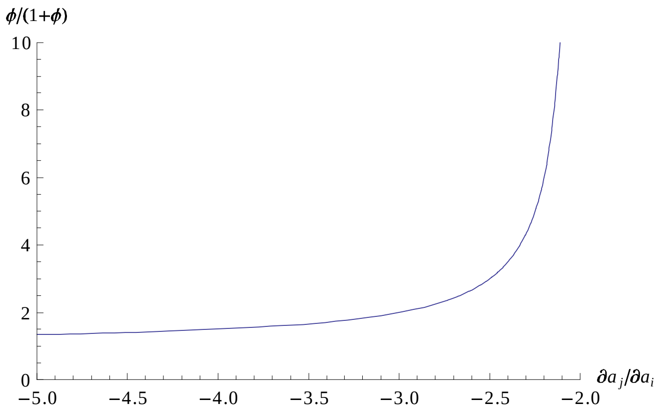

Figure 2: Social optimality when $\phi < -1$

depends on the sensitivity of the price change and the follower's reaction. Third, let us assume that the follower reacts with "strong" substitutability $\frac{\partial a_j}{\partial a_i} < -2$. Figure 2 represents the remaining branch of the hyperbola of $\frac{\phi}{1+\phi}$ for $\frac{\partial a_j}{\partial a_i} < -2$. From Figure 2, the aggregate emissions cap is lower than the level observed in the socially optimal benchmark ($\frac{\phi}{1+\phi}$ is above 1) and the simultaneous game. However, when $\frac{\partial a_j}{\partial a_i} \to -\infty$ the aggregate emissions cap converges towards the socially optimal level. Intuitively, as the leader increases its allocation, the follower reduces allocation proportionally, to such an extent, that the aggregate level of emissions is now lower than socially optimal.

In summary we have:

Proposition 3 *If domestic emissions caps are chosen sequentially, then:*

- When $\frac{\partial a_j}{\partial a_i} > 0$ the aggregate cap is larger than the socially optimal level and smaller than the simultaneous allocation.
- When $\frac{\partial a_j}{\partial a_i} = 0$ the aggregate cap is larger than the socially optimal level and is identical to the simultaneous allocation.
- When $\frac{\partial a_j}{\partial a_i} \in (-1, 0)$ the aggregate cap is larger than the socially optimal level and the simultaneous allocation.

- When $\frac{\partial a_j}{\partial a_i} < -2$ the aggregate cap is smaller than the socially optimal level and the simultaneous allocation.

For the rest of the paper, we focus on the most realistic scenario where $\phi > 0$. That is, to make comparisons between the simultaneous and sequential games, we focus on scenarios where the follower's reaction is either a complement or a "weak" substitute and simply refer to them as complements and substitutes. From Proposition 3, then, we consider the scenario where aggregate allocation is larger than the socially optimal level.

To further compare the results of simultaneous and sequential allocation, we follow Helm (2003) by denoting "low damage" regulators when the regulator experiences $p^* > \frac{\partial D_k(a)}{\partial a}$ and "high damage" regulators when $p^* < \frac{\partial D_k(a)}{\partial a}$. Given we know $\frac{\partial p^*}{\partial a} < 0$ from equation (6), it follows from equation (23) that in equilibrium,"low damage" regulators must be net sellers of permits and "high damage" regulators must be net buyers of permits. Intuitively, if "high damage" regulators increased their allocation, their damages would increase more than the payoff they would receive from doing so. Therefore they prefer to be net buyers of permits. Conversely, "low damage" regulators receive a higher price than their damage for each unit of allocation chosen, so would prefer to increase allocation and be a net seller of permits.

An interesting result occurs when we investigate the consequences of switching between a simultaneous game and a sequential game. In a sequential allocation game the leader can adapt it's allocation choice in full knowledge of the reaction of the follower. In fact, in certain circumstances the leader may completely alter it's behaviour between the simultaneous and sequential games. For $\phi > 0$, comparing (21) with $\phi = 1$ and $\phi \neq 1$ reveals that a regulator in a simultaneous game that switches to become a leader in a sequential game may have an incentive to alter its use of permits so that it changes from a net seller (buyer) to net buyer (seller). We find that:

Corollary 4 *If a regulator changes from a simultaneous to a leader in a sequential allocation then:*

(i) For $\phi \in (1,\infty)$, $\exists\ \phi^*$ *where* $\forall\ \phi \geq \phi^*$ *such that* $p^* > \dfrac{\partial D_i(a)}{\partial a}$ *and* $\dfrac{p^*}{\phi} < \dfrac{\partial D_i(a)}{\partial a}$ *and*

(ii) For $\phi \in (0,1)$, $\exists\ \phi^*$ *where* $\forall\ \phi \in (0,\phi^*]$ *such that* $p^* < \dfrac{\partial D_i(a)}{\partial a}$ *and* $\dfrac{p^*}{\phi} > \dfrac{\partial D_i(a)}{\partial a}$

Corollary (4) shows that, due to the additional information about the reaction of the follower, it is possible for net sellers (buyers) in the simultaneous allocation game to choose to become net buyers (sellers) in the sequential game. The intuition is clear. In case (i) the regulator is initially a net seller of permits then moves first to become the leader in the sequential game. If the follower in the sequential game chooses allocation in a complementarily fashion, then the follower will react to any increase in the leader's permit allocation by increasing it's own allocation which has the result of depreciating the permit price. Indeed as shown in Corollary (4) case (i), there will be a threshold value of the follower's reaction (ϕ^*) which will depreciate the price to such an extent that the leader actually chooses to become a net buyer of permits. In case (ii), a net buyer in the simultaneous game, moves first in a sequential game and we assume the follower in the sequential game chooses allocation as a substitute. For the leader, a threshold value of ϕ^* exists in which the substitution of permits is so low that, the price of permits becomes "too expensive" to buy permits and the leader switches to become a net supplier of permits instead.

Two other cases exist, (namely, $p^* > \frac{\partial D_i(a)}{\partial a}$ with $\phi \in (0,1)$ and $p^* < \frac{\partial D_i(a)}{\partial a}$ and $\phi > 1$) for which the combination of the leaders net supply/demand of permits and the followers reaction to the leader choice actually strengthens the behaviour of the leader, so that a regulator that becomes leader continues to be a net seller (buyer).

The choice of whether the leader decides to become a net buyer or seller of permits and consequently whether the follower will be a net supplier or buyer of permits, can also be viewed through the leader's marginal damage relative to the followers. This can be seen by subtracting (18) from (21) which gives:

$$\frac{\partial p^*}{\partial a} \cdot (a_i - e_i^*(a) - a_j + e_j^*(a)) + p^* \left(\frac{1-\phi}{\phi}\right) = \frac{\partial D_i(a)}{\partial a} - \frac{\partial D_j(a)}{\partial a} \tag{25}$$

Noting that, in equilibrium, $a_i - e_i^*(a) = -a_j + e_j^*(a)$ and denoting $\frac{\partial p^*}{\partial a} = p^{*'}$ equation (25) becomes:

$$2p^{*'} \cdot (a_i - e_i^*(a)) + p^* \left(\frac{1-\phi}{\phi}\right) = \frac{\partial D_i(a)}{\partial a} - \frac{\partial D_j(a)}{\partial a} \tag{26}$$

From equation (26) we have the following Proposition:

Proposition 5 *If* $\frac{\partial D_i(a)}{\partial a} > \frac{\partial D_j(a)}{\partial a}$ *then the leader announces an allocation so that:*

- *when* $\phi \in (0,1)$ *either (i)* $a_i < e_i^*$ *or (ii)* $a_i > e_i^*$ *such that* $\left|2p^{*'}(a_i - e_i^*(a))\right| < p^* \left(\frac{1-\phi}{\phi}\right)$
- *when* $\phi > 1$ *then* $a_i < e_i^*$ *such that* $2p^{*'}(a_i - e_i^*(a)) > \left|p^* \left(\frac{1-\phi}{\phi}\right)\right|$

If $\frac{\partial D_i(a)}{\partial a} < \frac{\partial D_j(a)}{\partial a}$ *then the leader announces an allocation so that*

- *when* $\phi \in (0,1)$ *then* $a_i > e_i^*$ *such that* $\left|2p^{*'}(a_i - e_i^*(a))\right| > p^* \left(\frac{1-\phi}{\phi}\right)$
- *when* $\phi > 1$ *then either (i)* $a_i > e_i^*$ *or (ii)* $a_i < e_i^*$ *such that* $2p^{*'}(a_i - e_i^*(a)) < \left|p^* \left(\frac{1-\phi}{\phi}\right)\right|$

Proposition (5) shows that not only does the leader choose to be a net supplier/ demander based on its relative marginal damage it also depends on the reaction of the follower. When $\frac{\partial D_i(a)}{\partial a} > \frac{\partial D_j(a)}{\partial a}$, it is intuitive that the leader, which has larger marginal damage, would aim to be a net buyer of permits. Yet in certain circumstances, although the leader has relative higher marginal damages, it will choose to increase allocation and become a net seller of permits. When the follower chooses allocation in a substitutable fashion, it may be optimal for the leader to increase its permit allocation even when it has relatively high marginal damages. The greater the substitution of permits from the follower the larger the increase in allocation from the leader. The leader will increase allocation as long as $\left|2p^{*\prime}(a_i - e_i^*(a))\right| < p^*\left(\frac{1-\phi}{\phi}\right)$.

Assuming that the leader has lower marginal damage than the follower $\frac{\partial D_i(a)}{\partial a} < \frac{\partial D_j(a)}{\partial a}$, it is feasible that the leader is a net seller of permits. Yet, when the follower selects allocation in a complementarily fashion, the leader may become a net buyer of permits. As the follower increases allocation (when the leader increase allocation), the permit price may be depreciated to such an extent that the leader becomes a net buyer of permits. The leader may choose to be a net buyer when $2p^{*\prime}(a_i - e_i^*(a)) < \left|p^*\left(\frac{1-\phi}{\phi}\right)\right|$.

This counter-intuitive result is due to the additional information the leader obtains about the follower. However, similar to D'Amato and Valentini (2006), for the special case when regulators simultaneously announce allocation caps ($\phi = 1$), the above result is simplified:

Corollary 6 *For $\phi = 1$,*

(i) If $\dfrac{\partial D_i(a)}{\partial a} > \dfrac{\partial D_j(a)}{\partial a}$ then regulator i announces an allocation so that $a_i < e_i^*$
(ii) If $\dfrac{\partial D_i(a)}{\partial a} < \dfrac{\partial D_j(a)}{\partial a}$ then regulator i announces an allocation so that $a_i > e_i^*$

When the leader takes the other regulator's choice as given, the regulator with the largest (smallest) marginal damage will always choose to be a net buyer (supplier) of permits. Therefore in the special case $\phi = 1$, the counter-intuitive result no longer holds. From corollary (6), it can easily be shown that regulator j will be be a net buyer (seller) when regulator i is a net seller (buyer) based on their relative marginal damages.

5 Conclusion

The purpose of this paper is to investigate the consequences of sequentially announcing domestic allocation caps in an international or federal-based tradable permit market. In the first stage of our game, regulators sequentially announce their domestic allocation caps to their representative firm. In stage two, their representative firm, given this information, selects a level of emissions to pollute in the perfectly competitive tradable permit market. To the best of our knowledge, no study has investigated the consequences of allowing regulators (or governments) to sequentially announce their allocation choices. However, it is apparent from existing tradable permit markets, such as the European Emissions Trading Scheme, that sequential allocation setting is prevalent (Zapfel 2007, p 23). The sequential setting of permit allocations may be a result, not of officially sanctioned rules or regulations in the tradable permit market, but due to heterogeneous factors that affect the timing of states' permit allocation selections, such as the different efficiency levels of state (government) bureaucracy. For this reason alone, it is important to understand the consequences of numerous regulators announcing domestic allocation caps at separate times.

We find that allowing regulators (or governments) to decide and announce their allocation cap is socially sub-optimal for sequential setting of permits (we also show this for the simultaneous case). We show that under the sequential setting of domestic emissions caps, the aggregate emissions is chosen closer too (further from) the socially optimal level when the follower's domestic allocation cap is complementary ("weakly" substitutable). In fact, the degree to which the follower changes allocation due to the leader's choice may, in certain circumstances, change the leader from being a net buyer (seller) of permits to a net seller (buyer).

Designers of tradable markets, need to be fully aware of the potential consequences of allowing regulators (or governments) to simultaneously or sequentially allocate permits. From the analysis it appears that simultaneous and sequential allocation setting will be socially sub-optimal. However, under a sequential allocation setting game, the leader may choose an allocation cap nearer the socially optimal level (compared to the simultaneous game) when the follower reacts to the leaders choice as if the allocation caps were complements.

As this appears to be the initial attempt at investigating the consequences of the sequential allocation choices, this model can be extended to include the presence of a third regulator. Many international, or federal-based tradable permit markets have "supra-governmental" agencies with power in these markets. For example, in the European Emissions Trading Scheme, the European Commission has the power to reject Member States' allocation plans. Also, the Intergovernmental Panel on Climate Change (IPCC) have possible powers to influence countries. In a federal-based tradable permit market, such as the Regional Greenhouse Gas Initiative (RGGI), it is feasible to consider the Environmental Protection Agency (EPA) may influence the proposed allocation choice of some states.

This paper suggests that previous attempts to model the strategic behaviour of regulators in international or federal-based tradable permit markets have neglected the important issue of timing. When designing tradable permit markets, one must consider the potential consequences for social optimality when domestic allocation caps are sequentially determined.

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