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Working Paper

A whiter shade of pale: On the political economy of regulatory instruments

Memorandum, No. 2004,29

Provided in Cooperation with:

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Suggested Citation: Baldursson, Fridrik M.; Fehr, Nils-Henrik M. von der (2004) : A whiter shade of pale: On the political economy of regulatory instruments, Memorandum, No. 2004,29, University of Oslo, Department of Economics, Oslo

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MEMORANDUM

No 29/2004

A Whiter Shade of Pale: on the Political Economy of Regulatory Instruments

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ISSN: 0801-1117

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This series is published by the
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A Whiter Shade of Pale: on the Political Economy of Regulatory Instruments

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December 4, 2004

Abstract

We consider an intertemporal policy game between changing governments that differ in their attitudes towards a particular feature of market outcomes, exemplified with environmental pollution. When in power, a government will choose policy instruments and set strictness of regulation with a view to influencing the policy of future, possibly different, governments. We demonstrate that a ‘brown’ government favours emission quotas over effluent taxes, as quotas establish property rights that are costly to reverse. Conversely, a ‘green’ government prefers to regulate by taxes, in order to limit the incentives of future ‘brown’ governments to ease regulations. Strategic behaviour tends to exaggerate policy differences (making ‘green’ governments ‘greener’ and ‘brown’ governments ‘browner’) compared to when such strategic considerations were not an issue.

Keywords: regulation, political economy, effluent taxes, tradable quotas, property rights, commitment, environmental management

JEL Classification codes: D81, D9, H23, L51, Q28, Q38

Acknowledgements: We thank Steinar Holden, Kalle Moene and Gylfi Zoega for useful comments. Financial support from NEMIEC – Nordic Energy Research is gratefully acknowledged.

1 Introduction

The economic analysis of regulation has typically taken government preferences as given and fixed. In the macroeconomic political economy literature, however, it has long been recognised that governments with different views will gain and lose power as time passes, and it has been convincingly argued that this has important consequences for policy decisions.¹ We show that the prospect of losing power to an opponent with different preferences has implications for the choice of regulatory instruments and their strictness. In particular, we establish a ‘whiter-shade-of-pale’ result: inherent policy differences are exaggerated by strategic considerations.

A basic idea in the macroeconomic political economy literature is that a government can influence its successor by changing ‘the constraints for succeeding governments with possibly very different preferences’ (Persson and Svensson, 1989, p. 342). In Persson and Svensson (1989), a conservative government forces a liberal successor to reduce spending by running a deficit and creating debt. In Alesina and Tabellini (1990), debt restricts a future government’s ability to spend money on a type of public good that the current government dislikes. Debt acts as a constraint in the sense that it commits later governments to allocate more funds to servicing debt and therefore there is less money available for public consumption.

The crux of these arguments is that future governments are committed to binding contracts with third parties; by borrowing, government creates debt that must be honoured by successors. This insight – that commitment is created by property rights – is particularly relevant for regulation, which often involves creation of such rights. For example, the allocation of quotas in environmental regulation involves an assignment of rights to private parties.² These rights may be permanent or limited in time depending on the terms set when quotas are allocated, but, while they are in place, ownership is protected by law. In particular, quotas cannot be expropriated without compensation to owners.

¹For recent reviews see Drazen (2000) and Persson and Tabellini (2000).

²It may be argued that when the public interest demands that the use of a common property resource be regulated allocation of rights of use, such as emission quotas, to agents that were already operating before the introduction of regulation merely amounts to a formalisation of previously existing, indirect property rights. Thus no new rights are created or transferred on the introduction of a quota system with grandfathering allocation. In this paper we assume that quotas are auctioned off to firms; hence, no grandfathering takes place.

This may be contrasted with price regulation.³ A tax on emissions is a flexible policy instrument: the tax rate can be changed in the budgetary process each year, and the tax may even be abolished without violating the rights of firms as protected by law.⁴ Future governments can adopt a higher or lower tax rate or change policy altogether and, for example, choose to regulate with emission quotas. Price regulation therefore does not commit present and future governments as strongly as quantity regulation.

A further important asymmetry has to do with public finances. If a quota system is in place, a relaxation of regulation (i.e. an increase in quota) results in an increase in revenues. If a tax regime is in place, however, the net increase in revenues from relaxing regulation (i.e. lowering the tax) is less, or even negative, as the gain from a larger tax base is counteracted by the lower tax rate. Conversely, tightening regulation involves a higher cost in the quota regime (of buying back quotas) than in the tax regime, as the reduction in tax base is compensated for by a higher tax rate.

We study, in a stylised two-party model, how these different characteristics of policy instruments affect government policy. The two types of government – ‘green’ and ‘brown’ – differ solely in their valuation of environmental damage of emissions. Both governments value non-distortionary revenues, such as income from quota sales or taxation of emissions, at the same marginal rate. In each period there is an election in which a government type is chosen with an exogenously given probability, independently of other events in the model. Governments subsequently decide on their policy – tax rates or quota allocations – and firms make their production and emission decisions. Governments minimise the present value of social costs of emissions and firms maximise profits. All agents entertain rational expectations.

In the tax regime it is easily seen that in our model there are no intertemporal linkages of periods; therefore, there is no scope for strategic behavior. However, due to

³The two classes of instruments – prices and quantities, or taxes and quotas – have been thoroughly studied in relation to a plethora of economic and environmental characteristics. While, in a static model, regulation by quotas and taxes is equivalent under certainty, Martin Weitzman showed in his seminal (1974) paper that with quadratic cost curves and uncertainty about marginal abatement costs, taxes, compared to quotas, become more attractive as a regulatory tool the greater is the slope of the marginal abatement cost function relative to the marginal environmental damage function. Weitzman’s result was followed up by Adar and Griffin (1976), Fishelson (1976) and Roberts and Spence (1976) and has been generalised and refined in a large literature. Recent contributions include Baldursson and von der Fehr (2004b,c).

⁴For the purposes of simplicity of exposition we shall assume that firms are the polluting agents.

the costs of distortionary taxation the optimal solution for each government is different from what it would be if the cost of public funds were disregarded. In the quota regime, we allow for a very flexible system of quotas, where a given government can issue separate quotas for every future period (such a system could be implemented through a portfolio of futures contracts, where there is a distinct contract for each future date). A government can change the aggregate amount of quotas outstanding for a particular period by buying or selling the required amount. We show that – as intuitively expected – prices for each distinct contract are decreasing in the aggregate amount of quotas allocated and brown governments always issue more quotas than green governments. Somewhat less intuitively, we find that, irrespective of its ‘colour’, a government will always allocate more quotas for a given period the higher the amount of quotas issued by a previous government. This is due to the asymmetric public finance properties of quotas discussed above. Furthermore, governments will exhibit ‘whiter-shade-of-pale’ behaviour. More specifically, in order to influence the behaviour of opponents, green governments will always reduce future quota allocations (i.e. the aggregate amount of outstanding futures contracts), whereas brown governments will increase them. Comparing the two types of instruments, we find that green governments prefer taxes while brown governments prefer quotas.

To illustrate the features of the model in a more concrete way than possible with general functional forms we also present an example where a closed form solution can be derived. Interestingly, the quota solution has a very simple form and may be implemented by a combination of rental and permanent quotas.

The flexibility inherent in our main quota setup may be criticised as being unrealistic. Transaction costs and costs of regulation may, for example, limit the available contract structure. We therefore consider a more restrictive framework where only permanent quotas are available. We have not been able to establish analytical results for this case. However, numerical analysis can easily be conducted. Analysis of an example with quadratic functional forms reveals that, again, governments will engage in exaggerated behaviour, trying to tie the hands of one another, generating fluctuations in emission limits and quota prices. The ‘whiter-shade-of-pale’ result is therefore seen to carry over to this more restrictive case.

The result that strategic motives exaggerate differences in behaviour between types of governments is apparently different from the results of Persson and Svensson and Alesina and Tabellini, where the desire to influence the policies of a successor makes governments more similar. We attempt to clarify the mechanism driving these seem-

ingly contradictory results by setting up a common, stylised framework that encompasses the essential features of the different models. We show that whether the behaviour of a government with respect to a particular activity is exaggerated or attenuated by strategic motives depends on the relationship between activity levels in different periods. In particular, current and future government spending are *intertemporal strategic substitutes* and therefore strategic motives will decrease differences between fiscal policies of governments of different types. Current and future quota allocations, however, are *intertemporal strategic complements* and therefore strategic motives will exaggerate differences between policies in this case.

2 Taxes and quotas

We now introduce the basic elements of our model and illustrate the fundamental public finance properties of taxes and quotas that are important in the analysis that follows.

We consider a model in which governments choose instruments and their levels of strictness. Firms, which are assumed to be infinitesimally small, identical and to take prices and other aggregate variables as given, are non-strategic participants in the game, responding only to the incentives created by the government so as to maximise their profits, but entertaining rational expectations about future developments. We take decisions of firms in goods and (non-environmental) factor markets, as well as their costs and profits prior to abatement activities, to be exogenous and given. In any given period all firms produce the same amount of pollutant prior to abatement, which we take to be equal to 1 without loss of generality. However, firms can abate at some cost: if a firm emits an amount y of pollutant the cost to the firm is $c(y)$, where c is a smooth function, decreasing in y (the smaller the emissions the larger the costs to the firm) and convex (unit costs of abatement are increasing in the amount of abatement $a = 1 - y$). Without loss of generality, we can take the mass of firms to be equal to 1 and, since firms are perfectly symmetric, aggregate emissions, denoted by Y , and aggregate cost of abatement, denoted by C , are equal to y and c , respectively. Since aggregate and firm level emissions and costs can be identified we do so and use the lower case letters for both variables in what follows.

In Figure 1, we have illustrated a simple setting in which emissions are regulated by a tax. Total emissions y are measured on the horizontal axis, while the tax rate t is measured on the vertical axis. Firms' marginal benefit from emitting y of the pollutant (derived from savings on abatement cost) is a downward-sloping function.

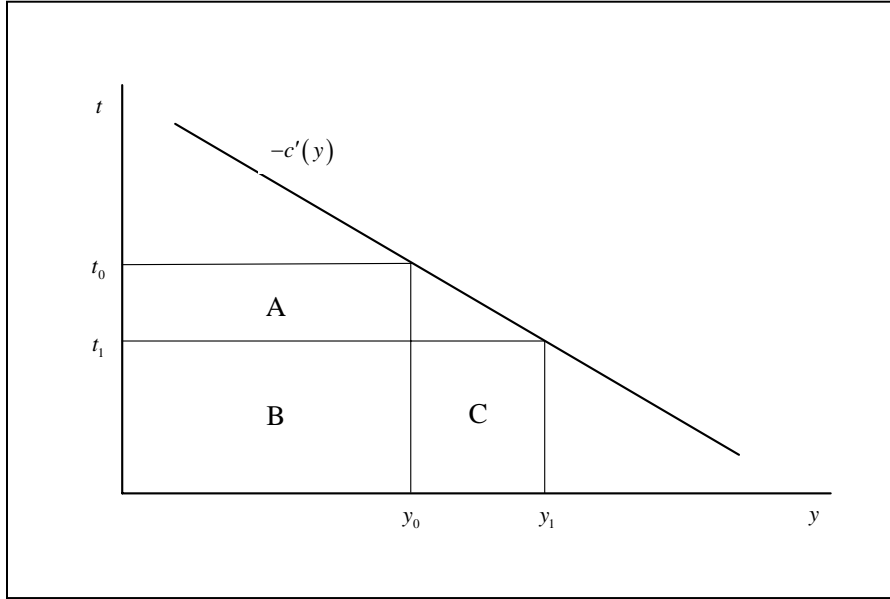


Figure 1: The tax case

Consequently, for a given tax rate total emissions can be read off the benefit curve; for example, if the tax rate is t_0 emissions are y_0 . Tax revenue is given by the area of a rectangle with height equal to the tax rate and length equal to the corresponding level of emissions; in particular, given the tax rate t_0 tax revenue is given by the area of $A + B$.

Consider the impact on tax revenues resulting from a change in the tax rate. If the tax rate is reduced from t_0 to t_1 tax revenue changes from $A + B$ to $B + C$. We may decompose the difference $C - A$ into a price effect and a quantity effect: on the one hand, a reduction in the tax rate leads to a reduction in revenues per unit of emissions; on the other hand, a lower tax rate increases emissions and hence broadens the tax base. The net effect is positive if the quantity effect (C) dominates the price effect (A), and vice versa. If we consider instead an increase in the tax rate from t_1 to t_0 we get the exact opposite result.

We next turn to Figure 2, which illustrates the corresponding case in which emissions are regulated by a (tradable) quota. In this setting, given the total quantity of quotas, the resulting quota price may be read off the benefit curve; for example, if the quota is q_0 the quota price becomes p_0 . Revenues obtained from selling this quantity of quotas equals the area $A + B$.

Consider then the effect on government revenues from increasing the supply of quo-

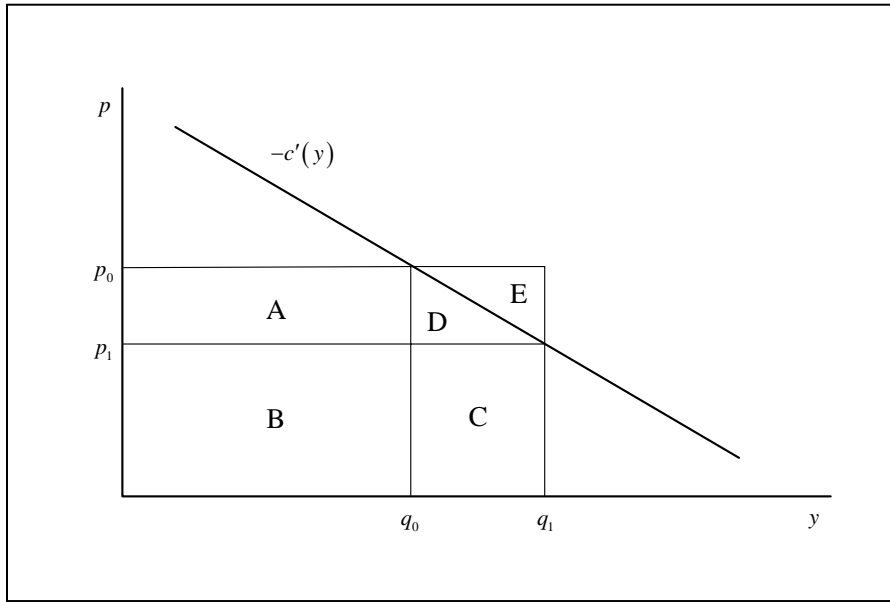


Figure 2: The quota case

tas. If more quotas are offered on the market, their market price falls.⁵ Consequently, if the quantity of quotas increases from q_0 to q_1 revenues increase by C . Conversely, in order to reduce the outstanding quantity of quotas, the government must raise the quota price so as to attract sales offers. A reduction in quotas, from q_1 to q_0 , therefore requires a government outlay of $C + D + E$. Whereas an increase of quotas raises revenues by C , a corresponding reduction costs $C + D + E$.

The above analysis suggests, therefore, that from a revenue point of view taxes and quotas are quite different. In particular, a tax instrument, as opposed to a quota instrument, is ‘flexible’ in the sense that the effect on government revenues is symmetric for upward and downward changes in the tax rate. In the quota case, on the other hand, a reduction in quotas has a larger impact on government revenues than a corresponding increase in quota supply.

Moreover, the attractiveness of changing regulation depends on both the choice of regulatory instrument and the direction of change. In particular, easing regulation is more attractive in the quota case than in the tax case; in the quota case revenues increase by C , while they increase by $C - A$ in the tax case. The reason for this

⁵This is a consequence of the assumptions that firms have rational expectations and quotas are tradable; the government is therefore restricted in its ability to undertake (intertemporal) price discrimination, cf. Coase (1972); see also Bulow (1982) and von der Fehr and Kühn (1994).

difference is that there is no price effect in the quota case (or, rather, the price effect is borne by the initial quota holders, not by the government). The opposite is true when environmental regulation is made stricter; then revenues are reduced by $A - C$ in the tax case, whereas the reduction is $C + D + E$ in the quota case.

This asymmetry means that it is more difficult (i.e. costly) to ease environmental regulation with a tax instrument in place, whereas tightening regulation is more difficult with a quota instrument. Therefore, we would expect a green government to prefer a tax (since this would commit a future brown government to a stricter level of regulation), whereas a brown government would prefer quotas (since these would commit a green government to a laxer level of regulation).⁶

3 The policy game

There are two types of government, green (G) and brown (B). These types differ in their valuation of environmental damage of emissions. This is formalised by different social damage functions which are assumed to be convex, smooth and increasing in aggregate emissions. The green government is assumed to value the costs of environmental damage higher than the brown, viz.

$$D^G(0) = D^B(0) = 0, \quad (1a)$$

$$D^G(y) > D^B(y), \text{ for all } y \in [0, 1]. \quad (1b)$$

The marginal value of public funds to the government, due to distortions elsewhere in the economy, is μ , assumed to be independent of the type of government.

In each period there are three stages. In the first stage there is an election and a government type is chosen. We assume this is a random event, probabilistically independent of other events; in particular, it is independent of policies chosen in other periods of the game. Thus a green government is elected with probability $\pi \in [0, 1]$ and a brown government is elected with probability $1 - \pi$.⁷

⁶Note that this result is derived under the assumption that governments care equally about revenues. When we observe that governments do differ in their attitudes towards taxes and quotas, this may however be due to their different revenue and distributational implications when quotas are grandfathered. It is consequently difficult to test directly this implication of our theory.

⁷Clearly this model can be generalised, e.g. to Markovian probabilities of transition where the probability of election of a given type of government depends on what type was in power prior to the election. Also, the actions of the government might be assumed to influence voter behavior and

In the second stage the current government sets tax rate or allocates quotas – depending on the prevailing regime – according to its preferences, taking into account possible events in later stages of the game. If a quota regime is in place, the government sets quotas for each period, present and future.⁸ Denote the amount of quotas set in period n for period $m \geq n$ by $q_{n,m}$. The aggregate amount of quotas held by firms can only be changed through transactions in the market place.⁹ Hence, if the target for the government in a given period m is higher than that set by a previous government, i.e. $q_{n,m} > q_{n-1,m}$, then the present government must auction quotas in the amount $q_{n,m} - q_{n-1,m}$. Conversely, if $q_{n,m} < q_{n-1,m}$ the government must buy back an amount of quotas $q_{n-1,m} - q_{n,m}$. A possible implementation of this regime is through future contracts; there would then be a separate contract for emissions at each future date m . If the aggregate amount of emissions embodied in contracts initially outstanding in Period n is larger than the government desires then additional contracts must be auctioned off; if the amount is smaller, then some future contracts must be bought back. If a tax regime is in place, however, then the government simply sets a tax rate t per unit of pollutant in each period. In principle, the government could announce tax rates for future periods. However, for reasons given in the previous section there are no intertemporal aspects to the tax regime and such announcements would have no commitment value. We may therefore disregard this possibility without loss of generality.

In the third stage firms decide on their abatement. We assume their choices are based on profit maximisation, or equivalently in our model, minimisation of the costs of abatement, subject to the regulatory constraints and costs they face.

the government's chances of re-election (see eg. Biais and Perotti, 2002). We follow the examples of Becker (1983) and the macroeconomics literature referred to in the Introduction in ignoring voter behavior and focus purely on the possibility of influencing an opponent's actions through strategic manipulation of state variables.

⁸For analytical convenience we assume that the amount of quotas for any given period can be varied independently of the amount of quotas available in other periods. One interpretation of this approach is that quotas last for one period only; however, at any given time such quotas can be issued for future periods. An alternative implementation is that quotas of different duration are issued.

⁹Quotas are assumed to be property perfectly protected by law. This is of course a strong assumption and rarely are property rights so perfectly enforced, see e.g. Rose (2000).

4 Tax regime

We first consider the case in which a tax regime is in place. Since tax revenues in a given period are independent of tax rates set at other times there is no intertemporal relationship between periods and hence we can consider each one in isolation.

Given a tax rate t , agents minimise their total private cost associated with emissions $c(y) + ty$, so that the first-order condition for optimal abatement is

$$-c'(y) = t. \quad (2)$$

By the convexity of c the second-order condition for cost minimisation is clearly satisfied.

Differentiating with respect to t on both sides we obtain a relationship between emissions and the tax rate:

$$\frac{dy}{dt} = -\frac{1}{c''(y)} < 0. \quad (3)$$

The government chooses the tax rate to minimise the net aggregate cost of emissions. This is given by the sum of damages and abatement costs less tax revenue multiplied by the marginal cost of funds to the government:

$$W^g(y, t) = D^g(y) + c(y) - \mu ty, \quad (4)$$

where $g \in \{G, B\}$ indicates the type of government in power. The government will minimise W^g subject to (2) above. The first-order condition for this problem may be written:

$$D^{g'}(y^g) + c'(y^g) = \mu t \left[1 - \frac{1}{\varepsilon^g} \right]. \quad (5)$$

Here y^g is the optimal level of abatement and

$$\varepsilon^g = - \frac{dy}{dt} \frac{t}{y} \bigg|_{y=y^g} = \frac{-c'(y^g)}{y^g c''(y^g)} > 0$$

is the elasticity of the level of abatement with respect to the tax rate. Hence, strictness of the tax policy depends on the elasticity ε^g :

$$D^{g'}(y^g) + c'(y^g) \geq 0 \iff \varepsilon^g \geq 1. \quad (6)$$

In other words, there is a tradeoff between emissions (abatement) and public finance concerns, and whether the optimal level of emissions exceeds or falls below the level that would have been efficient had emissions been the only concern depends on the relationship between the tax rate and revenues.

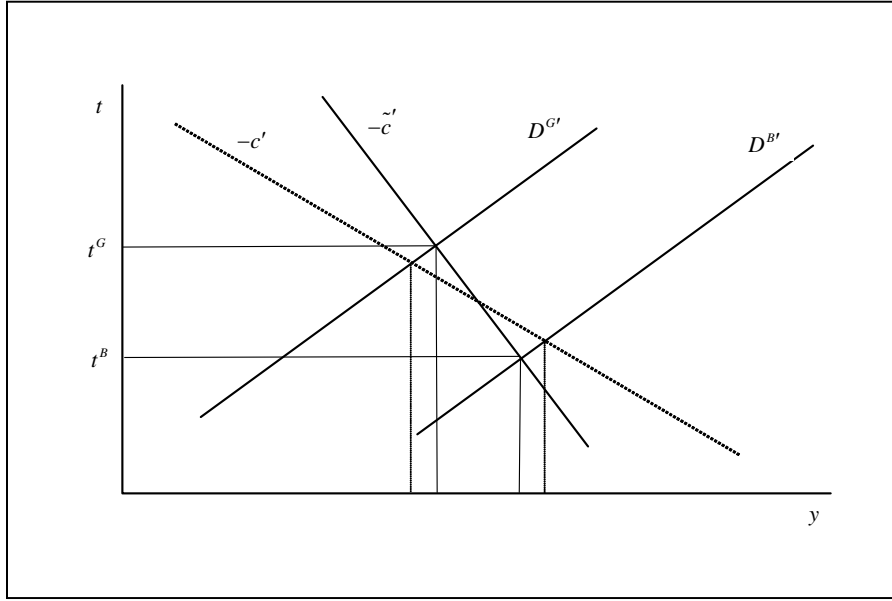


Figure 3: Green government chooses higher tax

Define the function $-\tilde{c}'$ by the relationship

$$-\tilde{c}'(y) = -c'(y) + \mu [-c'(y) - c''(y)y], \quad (7)$$

and note that the optimality condition (5) may be written as

$$D^{g'}(y^g) = -c'(y^g) + \mu t \left[1 - \frac{1}{\varepsilon^g} \right] = -\tilde{c}'(y^g). \quad (8)$$

Hence, the optimal tax rate equates marginal damage and marginal social benefits of emissions, $-\tilde{c}'$. Social benefits consist of private savings due to reduced abatement plus the social value of public funds. Note that the function $-\tilde{c}'(y)$ is independent of the type of government. Since $D^{B'} < D^{G'}$, it follows immediately that $y^G < y^B$. The natural relationship $t^G > t^B$ also follows, given a technical condition.¹⁰ This is illustrated in Figure 3.

Notice that in the Figure 3 policies of green and brown governments are brought closer together by their concern for public finance; that is, emissions differ less when public funds are costly ($\mu > 0$) than when cost of public funds is ignored ($\mu = 0$). This, however, is not a general result and depends on functional forms and parameter values.

¹⁰A sufficient condition is $yc''' > -c''$.

5 Quota regime

In Period m , given a price of quotas p_m , agents minimise their total private cost associated with the externality $c(y_m) + p_m y_m$, so that the first-order condition for optimal abatement is $-c'(y_m) = p_m$. Again, by the convexity of c , the second-order condition for cost minimisation is satisfied. Denote the quota for Period m set in that period by $q_m = q_{m,m}$. Furthermore, given the assumptions on c , for aggregate quota $q_m < 1$ the equilibrium level of abatement must satisfy $y_m = q_m$, and so the equilibrium price of quotas is given by

$$p_m = p(q_m), \quad (9)$$

where $p(q) = -c'(q)$.

At any given time, the government can allocate quotas for all future periods. The expected, present value of total costs as measured by government g in Period n are given by

$$V_n^g(Q_n; Q_{n-1}) = W_n^g(Q_n; Q_{n-1}) + \delta \{ \pi V_{n+1}^g(Q_{n+1}^G; Q_n) + [1 - \pi] V_{n+1}^g(Q_{n+1}^B; Q_n) \}, \quad (10)$$

where $Q_n = (q_{n,m})_{m=n}^\infty$ is a profile of quota allocations made in period n . The first term on the right-hand side is the net social cost of the externality in Period n :

$$W_n^g(Q_n; Q_{n-1}) = D^g(q_n) + c(q_n) - \mu p_n [q_n - q_{n-1,n}] - \mu \sum_{m=n+1}^\infty \bar{p}_{n,m} [q_{n,m} - q_{n-1,m}]. \quad (11)$$

The expression $p_n [q_n - q_{n-1,n}]$ – where $q_{n-1,n}$ is the quota for period n set in period $n-1$ – represents revenues from selling additional quotas in Period n . Correspondingly, the infinite sum represents the government's income from selling quotas for future periods. The equilibrium price of Period m quotas traded in Period n is given by the expected, discounted price of such quotas in Period $n+1$:

$$\bar{p}_{n,m} = \delta \{ \pi \bar{p}_{n+1,m}(q_{n+1,m}^G) + [1 - \pi] \bar{p}_{n+1,m}(q_{n+1,m}^B) \}.$$

The sum in (11) is guaranteed to converge since the expected discounted quota price tends geometrically to zero in m for a given n (observe that $0 < \delta < 1$ and $c'(y)$ is bounded for $y \in [0, 1]$).

The second term on the right-hand side of (10) is the discounted value of expected total costs in Period $n+1$ as valued by the present government. Note that the government rationally expects the quota policy of a green government in Period $n+1$ with

probability π and that of a brown government with probability $1 - \pi$. In both cases the present government values the chosen policy of future governments according to its own preferences.

Note that the problem of minimising $V_n^g(Q_n; Q_{n-1})$ can be broken up into sub-problems where, in each sub-problem, only the allocation for a specific period, say m , need be considered. First, it is clear from (10) and (11) that the choice of quotas for the current period, n , has no effect on allocation of quotas for future periods, and *vice versa*. The same obviously holds for period $n + 1$. When allocation of quotas for one period hence, $q_{n,n+1}$, is considered it therefore suffices to take the effect of that allocation on $q_{n+1,n+1}$ into consideration as well as the direct public finance effect $\bar{p}_{n,n+1} [q_{n,n+1} - q_{n-1,n+1}]$. This argument clearly generalises to an arbitrary number of periods into the future.

Due to this separability property of the problem allocations for each particular period may be considered in isolation. We start therefore by considering the government's problem of allocating quotas for the current period. This amounts to considering a single-period set up. We subsequently analyse the problem of allocating quotas for the next period, which requires a two-period set up. Finally, we consider allocation of quotas for an arbitrary number of periods into the future.

5.1 Single period

As pointed out above, when allocation of quotas for the current period is considered, allocation for future periods can be disregarded. In other words, it suffices to consider only those terms of (10) that relate to quotas for the current period. Therefore, the government's regulatory problem amounts to minimising

$$\widehat{W}_n^g(q_n; q_{n-1,n}) = D^g(q_n) + c(q_n) - \mu p_n [q_n - q_{n-1,n}] \quad (12)$$

subject to (9) above. The first-order condition for this problem may be written:

$$D'(q_n^g) + c'(q_n^g) = \mu p_n \left\{ 1 - \left[1 - \frac{q_{n-1,n}}{q_n^g} \right] \frac{1}{\varepsilon_n^g} \right\} \quad (13)$$

where

$$\varepsilon_n^g = - \frac{dy_n}{dp_n} \frac{p_n}{y_n} \bigg|_{y_n=q_n^g} = \frac{-c'(q_n^g)}{q_n^g c''(q_n^g)} > 0 \quad (14)$$

is the elasticity of the demand for quotas with respect to the price of quotas evaluated at the optimal quota.

The second-order condition for the cost-minimisation problem may be written:

$$D_g'' + [1 + 2\mu] c'' + \mu c''' [q_n - q_{n-1,n}] > 0.$$

This condition is satisfied if c''' is sufficiently small in absolute value; in particular, it is met if c is quadratic.

Note that, for given optimal quota q_n^g , the right-hand side of (13) is increasing in the amount of quotas issued in Period $n - 1$ for Period n , $q_{n-1,n}$. This suggests that the optimal level of emissions exceeds that under tax regulation, i.e. $y_n^g > y^g$, if $q_{n-1,n} > 0$. Indeed, differentiating the first-order condition for the government's problem, we find that the optimal quota is strictly increasing in amount of quotas issued in Period $n - 1$:

$$\frac{dq_n^g}{dq_{n-1,n}} = \frac{-\frac{\partial^2 \widehat{W}_n^g}{\partial q_{n-1,n} \partial q_n}}{\frac{\partial^2 \widehat{W}_n^g}{[\partial q_n]^2}} > 0. \quad (15)$$

The positive sign follows from the assumption that the second-order condition for the government's problem is satisfied (i.e. $\frac{\partial^2 \widehat{W}_n^g}{[\partial q_n]^2} > 0$), and the fact that $\frac{\partial^2 \widehat{W}_n^g}{\partial q_{n-1,n} \partial q_n} = \mu \frac{dp_n}{dq_n} = -\mu c''(q_n^g) < 0$. Note, however, that if $q_{n-1,n} = 0$, i.e. no quotas were issued for Period n in Period $n - 1$, then emissions in the quota regime and tax regime coincide and the optimal tax and the optimal price of quotas coincide also.

This result is easily understood by an examination of the first-order condition (13) which may be rewritten

$$D^{g'}(q_n^g) = -\tilde{c}'(q_n^g; q_{n-1,n}), \quad (16)$$

where

$$-\tilde{c}'(q; q_{n-1,n}) = -c'(q) + \mu \{-c'(q) - c''(q)[q - q_{n-1,n}]\} \quad (17)$$

is the marginal social benefit of emissions. The right-hand side of the first-order condition is shifted upwards by $\mu c''(q) dq_{n-1,n}$ if $q_{n-1,n}$ is increased by $dq_{n-1,n}$ and so the optimal quota increases. This is illustrated in Figure 4.

Similarly to the tax case, it is easily seen that a brown government issues more quotas than a green one, *ceteris paribus*; that is, $q_n^B(q_{n-1,n}) > q_n^G(q_{n-1,n})$. This is illustrated in Figure 5.

5.2 Two periods

We now consider the problem of allocating quotas for Period $n + 1$. As in the single-period case it suffices to consider those elements of (10) which are affected by allocation of quota for Period $n + 1$. The government's problem therefore amounts to minimising

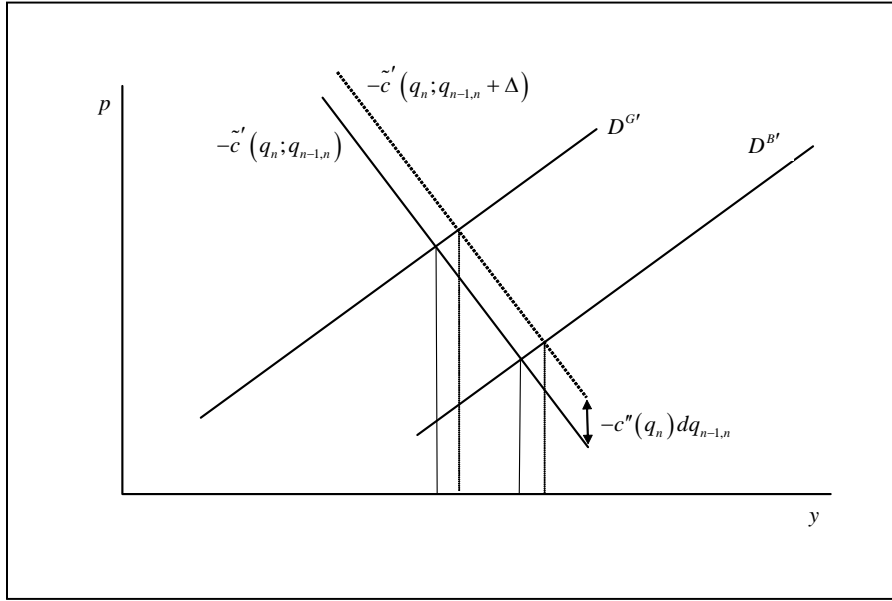
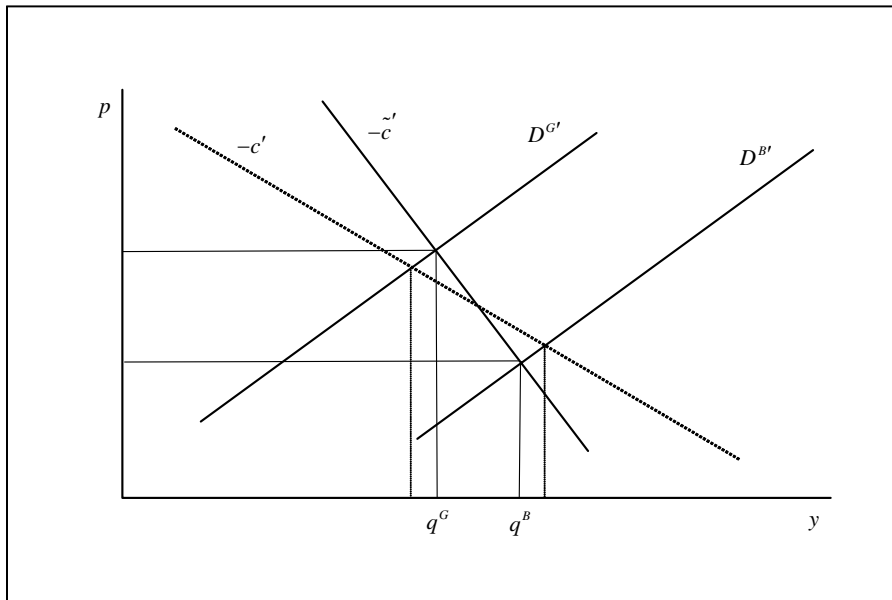
Figure 4: Effect of quotas allocated in earlier periods on Period n allocation

Figure 5: Brown government allocates more quotas

$$\begin{aligned} \widehat{V}_{n,n+1}^g(q_{n,n+1}; q_{n-1,n+1}) &= -\mu \bar{p}_{n,n+1} [q_{n,n+1} - q_{n-1,n+1}] \\ &\quad + \delta \left\{ \pi \widehat{W}_{n+1}^g(q_{n+1}^G; q_{n,n+1}) + [1 - \pi] \widehat{W}_{n+1}^g(q_{n+1}^B; q_{n,n+1}) \right\}. \end{aligned} \quad (18)$$

The first term on the right-hand side is the reduction in social costs due to revenues from sale of quotas for Period $n + 1$, where the equilibrium price of Period $n + 1$ quotas sold in Period n is given by the expected discounted price of quotas in Period $n + 1$:

$$\bar{p}_{n,n+1} = \delta \left\{ \pi p(q_{n+1}^G) + [1 - \pi] p(q_{n+1}^B) \right\}. \quad (19)$$

Note that $\bar{p}_{n,n+1}$ is a futures price; it is the price in the current period for a contract that gives the right to emit a unit of emissions in the next period.

The second term on the right-hand side of (18) is the discounted value of expected costs in Period $n + 1$ as valued by the present government.

First consider the problem from the point of view of a brown government; i.e. $g = B$. Differentiating (18) with respect to $q_{n,n+1}$, we find

$$\begin{aligned} \frac{\partial \widehat{V}_{n,n+1}^B}{\partial q_{n,n+1}} &= -\mu \left[\frac{d\bar{p}_{n,n+1}}{dq_{n,n+1}} [q_{n,n+1} - q_{n-1,n+1}] + \bar{p}_{n,n+1} \right] \\ &\quad + \delta \left\{ \pi \frac{d\widehat{W}_{n+1}^B(q_{n+1}^G; q_{n,n+1})}{dq_{n,n+1}} + [1 - \pi] \frac{d\widehat{W}_{n+1}^B(q_{n+1}^B; q_{n,n+1})}{dq_{n,n+1}} \right\} \\ &= -\mu \left[\frac{d\bar{p}_{n,n+1}}{dq_{n,n+1}} [q_{n,n+1} - q_{n-1,n+1}] + \bar{p}_{n,n+1} \right] \\ &\quad + \delta \left\{ \pi [D^{B'}(q_{n+1}^G) - D^{G'}(q_{n+1}^G)] \frac{dq_{n+1}^G}{dq_{n,n+1}} + \pi \mu p(q_{n+1}^G) + [1 - \pi] \mu p(q_{n+1}^B) \right\}. \end{aligned}$$

In the second equation of the above derivation we have made use of the identity $\widehat{W}_{n+1}^B(q; q_{-1}) = \widehat{W}_{n+1}^G(q; q_{-1}) + [D^B(q) - D^G(q)]$ and the Envelope Theorem applied to the Period $n + 1$ minimisation problem of governments. It now follows from (19) that the first-order condition for minimisation of $\widehat{V}_{n,n+1}^B$ is given by

$$-\mu \frac{d\bar{p}_{n,n+1}}{dq_{n,n+1}} [q_{n,n+1} - q_{n-1,n+1}] + \delta \pi [D^{B'}(q_{n+1}^G) - D^{G'}(q_{n+1}^G)] \frac{dq_{n+1}^G}{dq_{n,n+1}} = 0. \quad (20)$$

The first term on the left-hand side of (20) shows the marginal cost due to reduced government revenues from a change in prices when additional quotas are issued. From the previous section, we have $\frac{dq_{n+1}^G}{dq_{n,n+1}} > 0$. It follows that

$$\frac{d\bar{p}_{n,n+1}}{dq_{n,n+1}} = \delta \left\{ \pi p'(q_{n+1}^G) \frac{dq_{n+1}^G}{dq_{n,n+1}} + [1 - \pi] p'(q_{n+1}^B) \frac{dq_{n+1}^B}{dq_{n,n+1}} \right\} < 0.$$

The second term on the left-hand side of (20) represents the strategic effect of additional quota allocation. It is the marginal gain of a brown government due to induced increase in quota allocation of a green government, should such a government come into power.

Rearranging, the first-order condition (20) yields

$$q_{n,n+1}^B - q_{n-1,n+1} = \frac{\delta\pi}{\mu} [D^{B'}(q_{n+1}^G) - D^{G'}(q_{n+1}^G)] \frac{\frac{dq_{n+1}^G}{dq_{n,n+1}}}{\frac{d\bar{p}_{n,n+1}}{dq_{n,n+1}}} \geq 0.$$

Note that if $\pi = 0$, then $q_{n,n+1}^B = q_{n-1,n+1}$. In other words, if the brown government is sure to stay in power it will not change the amount of quotas that have been allocated for the next period. If, on the other hand, $\pi > 0$, then $q_{n,n+1}^B > q_{n-1,n+1}$ and the brown government will issue additional quotas. Additional quotas for a future period are therefore issued for strategic purposes only.¹¹ Since emissions are increasing in quotas brought into the period, cf. (15), this implies that if the brown government is reelected it will allow more emissions than it would have in the absence of strategic effects. In other words, strategic considerations will make a brown government ‘brownier’.

A corresponding result holds for a green government, *mutatis mutandis*. A derivation similar to the one above leads to

$$q_{n,n+1}^G - q_{n-1,n+1} = \frac{\delta[1-\pi]}{\mu} [D^{G'}(q_{n+1}^B) - D^{B'}(q_{n+1}^B)] \frac{\frac{dq_{n+1}^B}{dq_{n,n+1}}}{\frac{d\bar{p}_{n,n+1}}{dq_{n,n+1}}} \leq 0. \quad (21)$$

A green government always wants to reduce quotas for the future period $n+1$ (therefore, analogously to the case of a brown government, a green government will behave in a ‘greener’ manner - be more restrictive - than it would be in the absence of strategic considerations). As before this is entirely due to strategic reasons, in order to reduce emissions in the case that a brown government takes over. Note that, if $q_{n-1,n+1} = 0$ and $1 - \pi > 0$, then (21) implies $q_{n,n+1}^G < 0$, so a green government would like to issue negative quotas in this case, which amounts to borrowing quotas from firms. If such borrowing is not possible, then a green government would be constrained to setting quotas to zero. In what follows we shall disregard this constraint for analytical convenience.

¹¹In the absence of strategic effects, no further quotas should be issued in Period n for Period $n+1$. This is a consequence of the time-inconsistency problem studied in Baldursson and von der Fehr (2004a).

5.3 Multiple periods

In this section we show that results analogous to those above hold for allocation of quota for any given future period.

Proposition 1 *Assume that total costs are convex and that $0 < \pi < 1$. Then, for all m and $n \leq m$,*

- (i) $\frac{d\bar{p}_{n,m}}{dq_{n,m}} < 0$;
 - (ii) $\frac{dq_{n,m}}{dq_{n-1,m}} > 0$; and
 - (iii) $q_{n,m}^G < q_{n,m}^B$.
- Furthermore, for $n < m$,
- (iv) $q_{n,m}^G < q_{n-1,m} < q_{n,m}^B$.

Proof: See Appendix A.

The proposition first states that prices of quotas for current and future periods are decreasing in the amount of quotas allocated. The intuition for this result is that, as stated in (ii), an increase in quotas allocated for a certain period m leads to an increase in allocation for that period in all periods up to and including Period m . This happens in spite of the property stated in (iv) that a green government will always reduce quotas in periods before Period m . In other words, whereas a green government reduces quota allocations and a brown government increases them the amount of quotas available in any given period is greater the more quotas were issued in previous periods. Finally, as stated in (iii), independently of the history of quota allocation the available amount of quotas in the period when they are going to be used – and hence the level of actual emissions – is always smaller when a green government is in power than under a brown government.

From the proof of Proposition 1 (equation (31) in particular) it is easily seen that, whereas $q_{n,m}^G < q_{n-1,m} < q_{n,m}^B$ for $n < m$ when $0 < \pi < 1$, we have $q_{n,m}^B = q_{n-1,m}$ when $\pi = 0$ and similarly $q_{n,m}^G = q_{n-1,m}$ when $\pi = 1$. In other words, when governments are sure of reelection and therefore strategic motives are absent, they will not make any changes to quotas issued for future periods. Their actions will be restricted to allocating quotas in the period they are going to be used. In particular, if there are no outstanding quotas for future periods, then quotas are only going to be issued in the period of use in this case.

5.4 Example

In order to illustrate features of the model, we consider an example that allows for derivation of closed-form equilibrium solutions. As it turns out, solutions are both simple and intuitive; in particular, policies may be implemented by a combination of rental (one-period) and infinitely-lived (permanent) quotas.

The example has quadratic cost and damage functions, where the difference in government types is captured by a fixed difference in the perceived marginal damage of emissions:

$$\begin{aligned} c'(y) &= y - y_0, \quad y \leq y_0, \\ D^{g'}(y) &= d^g + y, \quad d^B = 0, \quad d^G = d > 0. \end{aligned}$$

From the first-order condition (13), we derive the optimal allocation of quotas for the current period for a brown and a green type of government, respectively:

$$\begin{aligned} q_n^B &= \frac{1}{2} \left[\frac{\mu}{1 + \mu} q_{n-1,n} + y_0 \right], \\ q_n^G &= \frac{1}{2} \left[\frac{\mu}{1 + \mu} q_{n-1,n} + y_0 - \frac{d}{1 + \mu} \right]. \end{aligned}$$

Similarly, from the first-order conditions (20) and (30), we derive the policy functions for allocations of quotas for future periods $m = n + 1, n + 2, \dots$:

$$\begin{aligned} q_{n,m}^B &= q_{n-1,m} + \frac{\pi d}{\mu}, \\ q_{n,m}^G &= q_{n-1,m} - \frac{[1 - \pi] d}{\mu}. \end{aligned}$$

Expected quota allocations, one period hence, become:

$$E_n \{q_{n+1}\} = \pi q_{n+1}^G + [1 - \pi] q_{n+1}^B = \frac{1}{2} \left[\frac{\mu}{1 + \mu} q_{n-1,n} + y_0 - \frac{\pi d}{1 + \mu} \right],$$

while for $m = n + 2, n + 3, \dots$

$$E_n \{q_{n+1,m}\} = \pi q_{n+1,m}^G + [1 - \pi] q_{n+1,m}^B = q_{n,m}.$$

Note that green governments will reduce quotas for a given future period m allocated in previous periods by $\frac{[1-\pi]d}{\mu}$. This happens with probability π . Similarly, brown governments will increase quotas for a given future period m allocated in previous periods by $\frac{\pi d}{\mu}$. This happens with probability $1 - \pi$. Quota allocation for Period

m in periods leading up to m therefore follows a random walk with zero mean (no drift/trend). This implies that a shift in allocation at some point will be carried over fully to other periods. Furthermore, since governments will increase/decrease quotas for all future periods by the same amount, all periods are treated symmetrically; they are, in a sense, equal. Note, however, that allocation in the current period is not determined in this fashion. In that case, quotas carried into the period enter with a weight of $\frac{1}{2} \frac{\mu}{1+\mu} < \frac{1}{2}$.

Governments can implement their desired policies by a combination of infinitely-lived and rental quotas. A brown government can issue an additional $\frac{\pi d}{\mu}$ of quotas that are valid for all future periods while adjusting current emissions by operations in a rental market for quotas to achieve its optimal goal of $y_n^B = \frac{1}{2} \left[\frac{\mu}{1+\mu} q_{n-1,n} + y_0 \right]$. Similarly, a green government can purchase $\frac{[1-\pi]d}{\mu}$ long-term quotas and adjust emissions by short-term operations to achieve emissions of $y_n^G = \frac{1}{2} \left[\frac{\mu}{1+\mu} q_{n-1,n} + y_0 - \frac{d}{1+\mu} \right]$.

Actual emissions follow a piecewise linear process. For example, when a brown government comes into power, emissions will immediately increase by $\frac{d}{2[1+\mu]}$ and then continue increasing by $\pi \frac{d}{2[1+\mu]}$ in subsequent periods, as long as it remains. Conversely, when a green government takes over, emissions will immediately fall by $\frac{d}{2[1+\mu]}$ and subsequently by $[1 - \pi] \frac{d}{2[1+\mu]}$.

6 Long-lived quotas

As explained above, we have chosen a framework with a very flexible structure of quotas. In this setup, quotas can be issued for any future period, independently of decisions made for other periods. In part, this is due to analytical convenience, but it also allows us to highlight the fundamental difference between taxes and quotas that only quotas involve commitment regarding future government actions by creation of property rights: allocations of quotas can only be changed by transactions on terms acceptable to market participants.

However, such flexibility is in many cases unrealistic. Due to transaction costs, costs of regulation or for other reasons contract structures are usually limited. Specifically, quotas of long duration give right to emit during a number of periods, from the present and into the future. This implies that strategic consideration will be tied to decisions about current emissions.

In this section we consider a model in which quotas are permanent. Note that

this is different from the example above. There infinitely lived quotas were a part of the equilibrium contract portfolio, but the government also had to rely on short-term (rental) market operations. In the set up considered in this section short-term operations are ruled out. Our results indicate that despite this contractual inflexibility – which implies that strategic considerations must be balanced against the costs of changing emissions – the basic results of the previous sections continue to hold: both types of government take on a deeper shade of colour.

The assumption that quotas are infinite in duration is easily accommodated in our previous framework. It is equivalent to the restriction that quotas allocated for future periods are equal to the allocation for the current period:

$$q_{n,m} = q_n \text{ for all } m \geq n. \quad (22)$$

The expected, present value of total costs as measured by government g in Period n are given by

$$V_n^g(q_n; q_{n-1}) = W_n^g(q_n; q_{n-1}) + \delta \left\{ \pi V_{n+1}^g(q_{n+1}^G; q_n) + [1 - \pi] V_{n+1}^g(q_{n+1}^B; q_n) \right\}. \quad (23)$$

Here

$$W_n^g(q_n; q_{n-1}) = D^g(q_n) + c(q_n) - \mu P_n [q_n - q_{n-1}], \quad (24)$$

where P_n is the value of quotas given by

$$P_n = p_n + \delta \left\{ \pi P_{n+1} (q_{n+1}^G) + [1 - \pi] P_{n+1} (q_{n+1}^B) \right\}, \quad (25)$$

and p_n is the rental price of quotas for a single period:

$$p_n = -c'(q_n). \quad (26)$$

Since the game is one of complete information with sequential moves it is clear there is a unique solution to it. It also seems clear that this solution is obtainable in the limit from backwards induction. Nevertheless, we have not been able to obtain an analytical solution, nor characterise it sufficiently well. Numerical solution, however, can easily be obtained for arbitrarily long time-horizons by backwards induction.

A computer program has been written which implements the backwards induction. The program can handle arbitrary functional forms for the cost functions c and D^g , but the results presented here are for the linear (marginal costs) case of the example

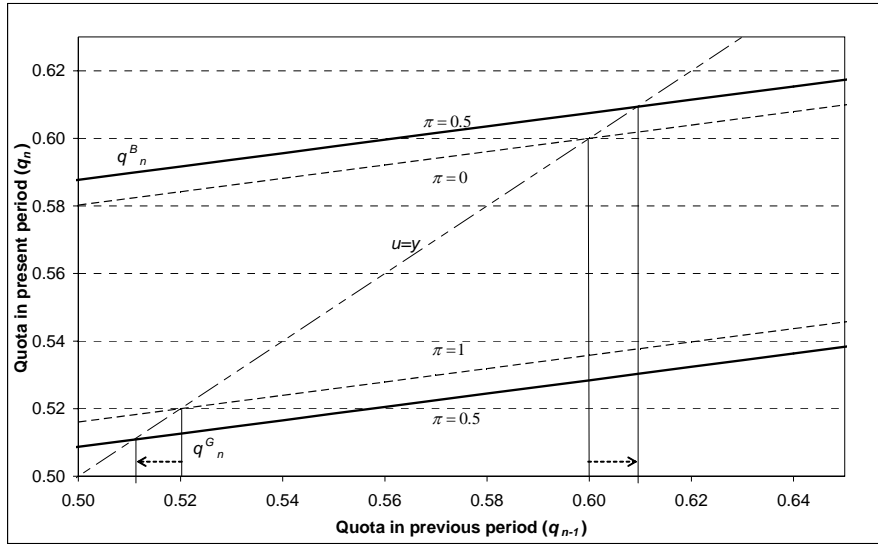


Figure 6: Policy functions

presented above. The specific parameter values used in the base case of the calculation are as follows: $\delta = 0.95$, $\mu = 0.5$, $\pi = 0.5$, $d = 0.2$ and $y_0 = 1$.

As seen in Figure 6, the policy functions $q^g(q_{n-1})$, $g = G, B$ are increasing in q_{n-1} and the policy function of a brown government lies strictly above that of a green government. The policy functions shift up with increasing π , i.e. when the probability of a green government increases. Hence, both types of governments will issue more quotas the higher the likelihood of a green government.

Furthermore, the whiter-shade-of-pale result holds here also: that is, a green government will issue fewer quotas when it is uncertain of holding onto power ($\pi < 1$) than when it is certain of staying in power ($\pi = 1$); conversely, a brown government will issue more quotas when it is uncertain of coming into power again ($\pi > 0$) than when it is certain to continue holding the reins ($\pi = 0$).

The dynamics of quota allocations may be envisaged from Figure 7. Clearly, states outside the interval $[q^G, q^B]$ are transitory, as illustrated at the far right-hand side of the figure (i.e. when starting above q^B and assuming that a brown government is in power). When starting inside the interval, the quota allocation will converge down towards q^G while a green government is in power (this is illustrated by the progression from q_0 to q_1 in two steps). When a brown government comes into power, there is an initial jump onto its policy function, followed by a more gradual convergence up towards q^B while it is in power (this is illustrated by the progression from q_1 to q_2 in

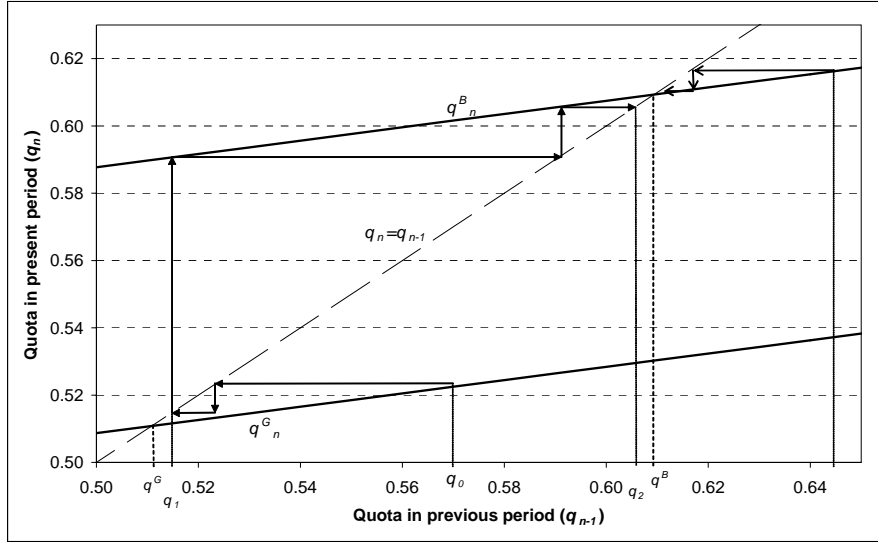


Figure 7: Quota dynamics

2 steps).

Consider the policy functions when a government of a particular type is sure to remain in power. These functions lie above, in the case of a green type, and below, in the case of a brown type, their counterparts when $\pi \in (0, 1)$. This implies that abrupt changes in quota allocations upon changes in government are larger than they would be if governments neglected the policy changes of future governments. As π increases, a brown government will raise its policy function to counteract the future policies of a green government. However, this pulls the brown type from the policy it would have preferred in the absence of strategic considerations and only serves a purpose if it ties the hands of a future green government. In our model the tying-effect arises from the marginal cost of funds assumption, i.e. that $\mu > 0$. A higher cost of public funds makes governments more conservative, in the sense that the adjustment towards the preferred long-term policy is more gradual.

A sensitivity analysis was carried out where one parameter was varied at a time. The qualitative nature of the numerical results described above was the same in all cases.

7 A taxonomy of policy games

The central result of our analysis – which also motivates the title of the paper – is that strategic motives exaggerate differences in behaviour between types of governments. This is contrary to results previously obtained in the political economy literature – such as in Persson and Svensson (1989) where the desire to influence the policies of a successor makes governments more alike. In Persson and Svensson a ‘conservative’ government runs deficits to induce a future ‘liberal’ government to reduce government spending, and *vice versa*. The results of Alesina and Tabellini (1990) are analogous. In this section we attempt to clarify the mechanism driving these results by setting up a common, stylised framework that encompasses the essential features of these models, as well as those of our own.

The expected cost of government $g = 1, 2$ is given by

$$V^g(q) = W^g(q) + \delta \{ \pi V^g(q^1) + [1 - \pi] V^g(q^2) \}.$$

where q is the current policy to be chosen, $q^g(x)$ is the optimal policy of the next government of type g , $x(q)$ is a state variable that depends on q and π is the probability of a government of type 1 in the next period. We order government types such that

$$W^{1'}(q) < W^{2'}(q) \text{ or } V^{1'}(q) < V^{2'}(q). \quad (27)$$

Define \hat{q}^g by $W^{g'}(\hat{q}^g) = 0$, $g = 1, 2$. We may interpret \hat{q}^g as the optimal choice of q for a government of type g in the absence of strategic considerations (i.e., $\pi = 0$ for $g = 1$ and $\pi = 1$ for $g = 2$). It is then immediate that $\hat{q}^1 > \hat{q}^2$.

In our set up, 1 denotes a brown government and 2 a green government, V is total costs, q is the amount of quotas, x is the amount of quotas carried over to the next period and q^g is the amount of quotas allocated by the next government. In our interpretation of the Persson-Svensson set up, 1 denotes a conservative government and 2 a liberal government, V is the negated government utility, q is the current level of public consumption, x is government debt and q^g is government spending in the next period.

We consider the behavior of a Type 1 government (analogous results are obtained for a Type 2 government). The first-order condition for the q that minimises V^1 is easily seen to be:

$$V^{1'}(q) = W^{1'}(q) + \delta \pi V^{1'}(q^2) \frac{dq^2}{dx} \frac{dx}{dq} = 0.$$

From (27) it follows that $V^{1'}(q^2) < 0$. Then (subject to necessary regularity conditions),

$$q^1 \geq \hat{q}^1 \Leftrightarrow \frac{dq^2}{dx} \frac{dx}{dq} \geq 0. \quad (28)$$

In our set up, $\frac{dq^2}{dx} > 0$ (more quotas carried over to the next period increases future quota allocations) and $\frac{dx}{dq} > 0$ (more quotas in the current period increases the amount of quotas carried over to the next period); consequently, $q^1 > \hat{q}^1$, i.e. a brown government takes on a darker shade. In the Persson-Svensson set up, $\frac{dq^2}{dx} < 0$ (higher debt reduces government spending) and $\frac{dx}{dq} > 0$ (higher public consumption increases government debt); consequently, $q^1 < \hat{q}^2$, i.e. conservative government runs a deficit.

As shown above, whether intrinsic characteristics of governments are exaggerated or attenuated by strategic motives depends on the sign of $s = \frac{dq^2}{dx} \frac{dx}{dq}$. When $s > 0$, an increase in the current decision variable q leads to an increase in future levels of the variable; intuitively, activity levels in different periods are *intertemporal strategic complements*. Analogously, if $s < 0$, activity levels in different periods may be thought of as *intertemporal strategic substitutes*.¹² In this terminology, our whiter-shade-of-pale result stems from the fact that emission quotas are intertemporal strategic complements. Conversely, the Persson-Svensson/Alesina-Tabellini results follow from the fact that current and future government spending are intertemporal strategic substitutes.

8 Conclusion

We have studied inter-temporal policy games between governments which differ in their attitudes towards a particular feature of market outcomes, exemplified by environmental pollution. We have argued that, from a strategic policy point of view, effluent taxes and quotas have very different characteristics. A tax is a flexible policy instrument that is easily adjusted; however, easing regulations by reducing the tax rate is costly in revenue terms. Quotas, on the other hand, are inflexible, as established property rights cannot be altered without the consent of the holder of these rights; however, given that some quotas have already been issued, easing regulations by issuing more quotas raises revenues. It follows that a ‘green’ government prefers taxes while a ‘brown’ government prefers quotas. Moreover, when a quota regime is established (which it will be once a ‘brown’ government has taken power) a ‘green’ government will purchase quotas,

¹²This terminology is inspired by that of Bulow, Geanakoplos and Klemperer (1985).

and a ‘brown’ government will sell quotas, with a view to influencing future policy; consequently, strategic considerations tend to exaggerate inherent policy differences.

The latter insight would appear to have wider implications: for example, a conservative government may carry privatisation further than it otherwise would in order to make it more costly for a future liberal government to extend the scope of the state; a minimalist government may narrow the tax base so as to reduce opportunities for future increases in tax revenues; and a government may appoint judges with extreme views (and perhaps younger and less experienced than what would otherwise be considered ideal) to counteract the impact of future appointments of judges with opposing leanings.

Our results may be contrasted with earlier work, in particular Persson and Svensson (1989) and Alesina and Tabellini (1990), where strategic motives move governments with different preferences closer in policy terms. We have shown how the different analyses can be placed in a common framework and that the direction of strategic effects depends on the nature of the policy variable under consideration. In particular, if activity variables in different periods are *intertemporal strategic substitutes* (such as current and future government spending) strategic motives will decrease differences between policies. If, however, activity variables in different periods are *intertemporal strategic complements* (such as current and future quota allocations) strategic motives will exaggerate policy differences.

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A Proof of Proposition 1

Fix a period m . The proof proceeds by induction backwards from m . First note that by the results of previous sections the claimed properties hold for $n = m$ and $n = m - 1$. It remains to show that they hold for n , given that they hold for $n + 1 < m$.

The expected, present value of costs as measured by government g in Period n and relevant to allocation of quotas in Period m may be written recursively as

$$\begin{aligned} \widehat{V}_{n,m}^g(q_{n,m}; q_{n-1,m}) &= -\mu \bar{p}_{n,m} [q_{n,m} - q_{n-1,m}] \\ &\quad + \delta \left\{ \pi \widehat{V}_{n+1,m}^g(q_{n+1,m}^G; q_{n,m}) + [1 - \pi] \widehat{V}_{n+1,m}^g(q_{n+1,m}^B; q_{n,m}) \right\} \end{aligned} \quad (29)$$

where $\widehat{V}_{m,m}^g(q_m; q_{m-1,m}) = \widehat{W}_m^g(q_m; q_{m-1,m})$. The first term on the right-hand side is the reduction in social costs due to revenues from sale of quotas for Period m , where the equilibrium price of Period m quotas traded in Period n is given by the expected discounted price of such quotas in Period $n + 1$:

$$\bar{p}_{n,m} = \delta \left\{ \pi \bar{p}_{n+1,m} (q_{n+1,m}^G) + [1 - \pi] \bar{p}_{n+1,m} (q_{n+1,m}^B) \right\}.$$

Differentiating (29) with $g = B$ with respect to $q_{n,m}$, we find

$$\begin{aligned}
\frac{\partial \widehat{V}_{n,m}^B}{\partial q_{n,m}} &= -\mu \left[\frac{d\bar{p}_{n,m}}{dq_{n,m}} [q_{n,m} - q_{n-1,m}] + \bar{p}_{n,m} \right] \\
&\quad + \delta \left\{ \pi \frac{d\widehat{V}_{n+1,m}^B(q_{n+1,m}^G; q_{n,m})}{dq_{n,m}} + [1 - \pi] \frac{d\widehat{V}_{n+1,m}^B(q_{n+1,m}^B; q_{n,m})}{dq_{n,m}} \right\} \\
&= -\mu \left[\frac{d\bar{p}_{n,m}}{dq_{n,m}} [q_{n,m} - q_{n-1,m}] + \bar{p}_{n,m} \right] \\
&\quad + \delta \left\{ \pi \left[\frac{d\widehat{V}_{n+1,m}^B(q_{n+1,m}^G; q_{n,m})}{dq_{n+1,m}} \frac{dq_{n+1,m}^G}{dq_{n,m}} + \mu \bar{p}_{n+1,m} \right] + [1 - \pi] \mu \bar{p}_{n,m} \right\} \\
&= -\mu \frac{d\bar{p}_{n,m}}{dq_{n,m}} [q_{n,m} - q_{n-1,m}] + \delta \pi \frac{\partial \widehat{V}_{n+1,m}^B(q_{n+1,m}^G; q_{n,m})}{\partial q_{n+1,m}} \frac{dq_{n+1,m}^G}{dq_{n,m}}.
\end{aligned}$$

By the induction hypothesis, we have $\frac{d\bar{p}_{n+1,m}}{dq_{n+1,m}} < 0$ and $\frac{dq_{n+1,m}}{dq_{n,m}} > 0$, and hence we obtain

$$\frac{d\bar{p}_{n,m}}{dq_{n,m}} = \delta \left\{ \pi \frac{d\bar{p}_{n+1,m}}{dq_{n+1,m}} \frac{dq_{n+1,m}^G}{dq_{n,m}} + [1 - \pi] \frac{d\bar{p}_{n+1,m}}{dq_{n+1,m}} \frac{dq_{n+1,m}^B}{dq_{n,m}} \right\} < 0.$$

Furthermore, given that $q_{n+1,m}^G < q_{n+1,m}^B$ and $\widehat{V}_{n+1,m}^B$ is convex, we have $\frac{dV_{n+1,m}^B(q_{n+1,m}^G; q_{n,m})}{dq_{n+1,N}} < 0$. From the first-order condition

$$\frac{\partial \widehat{V}_{n,m}^B}{\partial q_{n,m}} = -\mu \frac{d\bar{p}_{n,m}}{dq_{n,m}} [q_{n,m} - q_{n-1,m}] + \delta \pi \frac{\partial \widehat{V}_{n+1,m}^B(q_{n+1,m}^G; q_{n,m})}{\partial q_{n+1,m}} \frac{dq_{n+1,m}^G}{dq_{n,m}} = 0 \quad (30)$$

we then obtain

$$q_{n,m}^B - q_{n-1,m} = \frac{\delta \pi}{\mu} \frac{\partial \widehat{V}_{n+1,m}^B(q_{n+1,m}^G; q_{n,m})}{\partial q_{n+1,N}} \frac{\frac{dq_{n+1,m}^G}{dq_{n,m}}}{\frac{d\bar{p}_{n,m}}{dq_{n,m}}} > 0 \quad (31)$$

Correspondingly, we have

$$q_{n,m}^G - q_{n-1,m} < 0.$$

Finally,

$$\frac{dq_{n,m}^g}{dq_{n-1,m}} = -\frac{\frac{d^2 \widehat{V}_{n,m}^g}{dq_{n-1,m} dq_{n,m}}}{\frac{d^2 V_{n,m}^g}{[dq_{n,m}]^2}} = \frac{-\mu \frac{d\bar{p}_{n,m}}{dq_{n,m}}}{\frac{d^2 V_{n,m}^g}{[dq_{n,m}]^2}} > 0.$$

QED