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ORIGINAL ARTICLE

Enforcement and environmental quality in a decentralized emission trading system

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Abstract Should the powers of monitoring compliance and allocating tradeable emissions allowances be appointed to a unique supranational regulator or decentralized to several local regulators? To answer this question, we develop a two stage-two country game where environmental regulators set the amount of emission allowances and the level of monitoring effort to achieve full compliance while the regulated firms choose actual emissions and the number of permits to be held. Various, possibly conflicting, spillovers between countries arise in a decentralized setting. We show that decentralization is socially harmful if no asymmetry among institutional settings is introduced and can be suboptimal even when decentralization features lower monitoring costs than a centralized setting. Lower monitoring costs are therefore *necessary*, but *not sufficient*, to justify decentralization. Also, our analysis reveals that welfare can be higher under decentralization even if the corresponding environmental quality is worse than under centralization. Indeed, better environmental quality is *sufficient* but *not necessary* for higher welfare under decentralization. Finally, we discuss how these results can provide a theoretical rationale for the recent evolution of the EU ETS design.

Keywords Emissions trading · Environmental federalism · Enforcement · Monitoring cost

JEL Classification H70 · Q58

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1 Introduction

The degree of decentralization of public policies is a controversial topic. Indeed, while the so called "principle of subsidiarity" claims that it would be better to decentralize to the jurisdictional level which is closer to the preferences of consumers and/or producers, in several circumstances environmental policies may represent important exceptions to this principle (Oates 1999). We deal with this issue with a specific focus on international emissions trading. More specifically we want to assess to what extent the powers of monitoring compliance and allocating emissions permits should be appointed to a supranational authority or delegated to the single states.

The issue at hand is both politically relevant and theoretically appealing. A significant evidence of this importance may be found in the quite heated debate on the decentralized nature of the EU emission trading system (ETS) which is characterized by "...the European Commission making certain basic decisions concerning the structure of and participation in the system..." and "...Member States deciding their national cap level; allocating the country's permits (allowances) to sources; creating institutions to monitor, report, and verify their emissions..." (Kruger et al. 2007, p. 112). Nonetheless, the EU ETS is widely recognized to be "a classic cap-and-trade system" (Ellerman 2008) where permits are traded at the Union level and, even if single member states have a certain degree of freedom in specifying the total amount of permits to be allocated within their boundaries, the European Commission has the ultimate power to request countries to modify their allocation plans. However, at least in the first two phases of the EU ETS functioning (2005–2007 and 2008–2012), the flexibility left to the member states in setting their national emissions caps was significant (see, for instance, Zapfel 2007). Such a degree of freedom mostly depended on the incomplete coverage of the emissions trading mechanism with respect to the Kyoto targets that the Burden Sharing Agreement assigned to the single member states. In other words, member states, when deciding their national caps, can consider emission permits jointly with the other abatement measures that they are planning to adopt. In 2008, the EU Commission itself recognized that "...a system based on national cap-setting does not provide sufficient guarantees that the emission reduction objectives endorsed by the European Council in March 2007 will be achieved..." (European Commission 2008 , p.7) and, as a consequence, proposed to implement, after 2013, a EU wide cap which eventually has been introduced by Directive 2009/29/CE. The establishment of a EU wide cap in the Directive does imply taking the EU ETS closer to a more standard *centralized* emission trading system—like the SO2 trading system implemented in the US—with, however, monitoring and enforcement duties left to single states.

By analyzing this subject on a more theoretical ground, it can be plainly shown that in a decentralized ETS (DETS) *à la* Helm (2003) member states tend to over-allocate permits with respect to the optimal allocation that would emerge under a centralized ETS (CETS) (D'Amato and Valentini 2009).[1] In that framework, however, enforcement issues are not taken into account and, therefore, one could argue

[1] A consequence of over-allocation is a lower than optimal permits price. In fact, Ellerman and Buchner (2008) investigate whether the large reduction of permits price observed during the first trading phase of the

that the inefficiency due to over-allocation might be balanced if some monitoring cost advantage exists in favor of single states. Indeed, the existence of monitoring cost advantages under decentralization finds a theoretical support in the presence of centralized diseconomies of scale in administration and technical expertise (Butler and Macey 1996) as well as a "real life" support in the EU choice to decentralize monitoring. Therefore, it is interesting to investigate whether, and under what circumstances, these considerations can contribute to sustain the choice of a DETS to control pollution.

To deal with this issue we use a two stage game played by environmental regulator(s) and polluting industries within two alternative institutional frameworks, namely a CETS and a DETS. More specifically, a single supranational regulator (under a CETS) or two independent regulators (under a DETS) choose the emission caps and set the level of monitoring effort to achieve full compliance in the first stage and, in the second stage, each firm observes the monitoring effort and the emission caps selected by regulator(s) and chooses the number of permits to be held as well as emissions' level. Our comparison between these two "extreme" institutional settings also provides useful insights in the investigation of a "mixed" emissions trading system like the "new" EU ETS, introduced by Directive 2009/29/CE where monitoring is decentralized but the cap is set at the centralized level.

Our results suggest that cost differential in monitoring for compliance can imply lower emissions and greater welfare under a DETS than under a CETS. Nevertheless we also show that cost advantage in favor of single states' regulators is not sufficient to justify decentralization. More specifically, when there is no asymmetry between countries and between centralized and decentralized regulators, full decentralization always leads to higher emissions and lower welfare. Similarly, when the monitoring cost differential is in favor of fully decentralized regulators but it is not sufficiently high, yet a DETS can be justified neither in terms of environmental quality nor by a more general social welfare analysis. Environmental quality is higher under decentralization only if the monitoring cost differential is sufficiently high in favor of decentralized regulators. However, for specific functional forms used to carry out some additional welfare analysis, we show that a better environmental quality is not a necessary condition for higher welfare under the DETS. In other words, a higher emissions level is not, by itself, proof that decentralization of emissions trading is bad, as decentralization could be a good way to tackle monitoring problems in a cost effective way. On the other hand, a better environmental quality under the DETS is a sufficient condition for higher welfare under the same regime. Finally, the "mixed" emissions trading system with decentralized monitoring duties and a centralized emissions cap takes out the best of the CETS and the DETS and may outperform both of them in terms of environmental quality and aggregate social welfare.

Most of these findings depend on a number of conflicting effects that an increase in permits endowments in one country causes to the other country and that a decentralized regulatory mechanism cannot internalize or account for. Four effects, related

Footnote 1 continued
EU ETS is an evidence of over-allocation but they cannot dismiss the alternative hypothesis that, instead, this is mostly due to pollution abatement.

to changes in the initial allocation of permits in any country, are particularly relevant: the first one, that cancels out on aggregate, is a *distributional spillover* affecting the other country's revenue from permits selling, or cost of permits buying. The second effect, labelled as *pollution spillover*, causes lower environmental quality and lower welfare in the other country; the third one, named *enforcement spillover*, implies that a lower enforcement effort is needed in the other country; finally, we have a *monitoring cost effect* that may cause ambiguous consequences on environmental quality and welfare of the other country, depending on the sign of the asymmetry in monitoring cost between the centralized regulator and the decentralized ones.

A crucial assumption of this article is that, both under a DETS and under a CETS, monitoring is set to achieve full compliance. Indeed, after the seminal paper by Malik (1992), other theoretical papers have assumed full compliance to deal with emission trading issues (Stranlund and Chavez 2000; Chavez and Stranlund 2003).[2] This assumption is, in our view, close to actuality. Support for the full compliance assumption comes from the US SO_2 trading system (see Svendsen 1998) and, also, from the enforcement performance under the EU ETS in the first trading phase (See European Commission 2006, p. 8).

2 Literature review

Two strands of literature deal with questions which are closely related to the issue analyzed in this article. The first one is connected to the so called "environmental dumping" as in Barrett (1994) and Ulph (1996, 1998, 2000). These papers show how national regulators attempt to relax environmental policy in order to secure to domestic firms competitive advantages in international markets. Some more recent papers which are close in some sense to the "environmental dumping" literature deal specifically with emission trading. Among them Helm (2003) analyzes the allocation of emission permits under two alternative regulatory regimes, namely with and without the possibility of trading permits. In his paper Helm finds that the possibility of trading may induce more pollution since the higher number of permits chosen by environmentally less concerned countries may offset the choices of the more concerned ones. D'Amato and Valentini (2009) extend the analysis developed by Helm (2003) by considering also the case where the initial allocation of tradeable permits may be chosen cooperatively: they first show that a decentralized allocation of permits always results in a lower than optimal price of permits, as well as in an aggregate emission target which is larger than the socially optimal target that would arise under a centralized solution; then, by showing that some countries might not consent to a centralized solution, they provide a possible theoretical rationale behind decentralization. Our modelling strategy follows the one adopted by these papers but regulator(s) do not only choose the amount of allowances to be issued but also the level of monitoring and enforcement effort to be devoted to achieve full compliance.

Our article is also strictly related to the strand of literature on enforcement under emission trading systems starting with Malik (1990) and Keeler (1991). These two

[2] For a deeper discussion on the optimal degree of compliance see Stranlund (2007).

papers examine the consequences of endogenizing monitoring and enforcement within a permits market and conclude that efficiency properties of emissions trading might not hold when compliance issues are accounted for. In a subsequent work, Malik (1992) includes explicitly enforcement costs in the comparison between incentive based policies and standard command and control instruments, and concludes that the ranking between the two kinds of instruments is not obvious in such a setting.

Many other papers contributed to the literature on enforcement under emissions trading in several respects[3] but, to our knowledge, the only other paper that investigated explicitly the consequences of decentralization in an international setting where the choice of enforcement effort is accounted for is Silva and Zhu (2008). These authors model an international ETS featuring decentralized regulatory and enforcement authorities and two supranational entities in charge of determining international lump sum transfers and choosing fines for noncompliant regulated agents. Their analysis shows that, in the presence of costly enforcement, a properly designed decentralized setting can replicate the first best. We depart from Silva and Zhu (2008) both because we analyze a different institutional setting where no interregional income transfers are implemented, and because the results in Silva and Zhu rest on binding budget constraints faced by decentralized authorities. The main driving forces of our conclusions rely, instead, on enforcement related spillovers.

An argument based on enforcement spillovers is used by Sigman (2010) when she deals with the issue of the optimal "scale" of emissions trading in presence of enforcement costs which are heterogeneous across market participants: in particular, Sigman shows that a "broad" ETS (i.e. including also sources featuring high enforcement costs) can be better than a narrow one because the broadening of the market might reduce the equilibrium price and, therefore, decrease the needed enforcement effort to achieve compliance. Sigman, however, does not examine the international dimension of emissions trading and she focuses on the "scale" of ETS rather than on its degree of decentralization.

The rest of the article is organized as follows. The main features of the model are presented in the next section. Section 4 derives the solutions of the games defined under both the decentralized and the centralized setting and presents a number of results based on comparative statics. The centralized and the decentralized regimes are compared in Sect. 5 in terms of both environmental quality and social welfare. Finally, Sect. 6 concludes.

3 The model

We analyze a stylized model representing an international context formed by two countries labelled as A and B. In each country i $(i = A, B)$ there are a large number of identical firms. By normalizing to 1 the number of firms in each country, we deal with one "representative" firm in each country (firm A and firm B). We model two

[3] See, among the others, van Egteren and Weber (1996), Stranlund and Dhanda (1999), Stranlund and Chavez (2000), Chavez and Stranlund (2003), Stranlund et al. (2005), Murphy and Stranlund (2006) and Stranlund (2007).

alternative institutional frameworks, namely a decentralized emissions trading system (DETS) and a centralized one (CETS). Under the DETS, we have a national environmental regulator in each country i $(i = A, B)$ while, under the CETS there is a single supranational regulator operating at the international level.

Before defining the interactions between the firms and the regulator(s), let us define the following variables: e_i is the level of actual pollution generated by firm i which is assumed to be uniformly mixing; $\overline{e}_i$ is the initial endowment of permits received by firm i; we also label $\overline{e} = \overline{e}_A + \overline{e}_B$; q_i is the level of allowed emissions, that is, the level of permits held by firm i; $v_i = e_i - q_i$ is the level of violation that is chosen by firm i: when $v_i = 0$ there is no violation and the firm is perfectly compliant, while the firm is non compliant whenever $v_i > 0$;[4] u_i is the level of monitoring effort in country i; finally, p is the international competitive price of permits.

The interactions between the two firms and the regulators are characterized by the following two stage games of complete (but imperfect) information defined separately for the DETS and the CETS.

3.1 The two stage game under the DETS

First stage: Each regulator i $(i = A, B)$ chooses the level of emissions permits allocated to firm i $(\overline{e}_i)$ in order to maximize the social welfare of country i defined as:

$$W_i = \pi_i - \psi_i - D_i \tag{1}$$

where π_i is the expected gross profit of firm i that will be better defined when describing the second stage, $\psi_i = \psi_i(u_i)$ is the cost of monitoring firm i under decentralization, with $\frac{d\psi_i}{du_i} > 0$ and $\frac{d^2\psi_i}{du_i^2} \geq 0$, while $D_i = D_i\,(e)$ is the damage to country i caused by total pollution e (defined as $e = e_A + e_B$); we finally assume $\frac{dD_i}{de} > 0$ and $\frac{d^2D_i}{de^2} > 0$. The level of monitoring effort (u_i) is set in order to induce firm i to be fully compliant.
Second stage: Each firm i $(i = A, B)$ chooses actual emissions (e_i) and permits holding (q_i) in order to maximize its expected net profit

$$\Pi_i = \pi_i - N(u_i, v_i) = B_i - p(q_i - \overline{e}_i) - N(u_i, v_i), \tag{2}$$

where $B_i = B_i(e_i)$ is a strictly increasing and concave function of benefits deriving from emissions (excluding permits and fine payments) and $p(q_i - \overline{e}_i)$ is the sum of money the firm spends (earns) if it is a net buyer (seller) of permits; given competitiveness in the permits market, p is exogenously faced by firms. $N(u_i, v_i)$ represents firm i's expected fine function[5] which is assumed to be symmetric across countries, coherently with existing institutional arrangements (i.e. the EU ETS), increasing in the violation, i.e. $\frac{\partial N}{\partial v_i} > 0$, and in the degree of monitoring, i.e. $\frac{\partial N}{\partial u_i} > 0$. The penalty

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[4] We reasonably assume, as it is standard in the literature (see, for example, Stranlund and Dhanda 1999) that overcompliance, that is $v_i < 0$, never takes place.

[5] We assume, as in Malik (1990), that the firm is audited in an unexpected way; also, it cannot react by varying permits holding after auditing has taken place.

for no violation is 0, i.e. $N(u_i, 0) = 0$, for any effort level. We also impose that $\frac{\partial^2 N(u_i, v_i)}{\partial v_i^2} \geq 0$, which implies that the fine increases with the violation at a non decreasing rate. Finally, $\frac{\partial N(u_i, v_i)}{\partial u_i \partial v_i} > 0$, that is, the marginal increase in expected penalty due to an increase in the violation increases with monitoring effort.

It is worthwhile to note that the expected fine is a net transfer from the firms to the regulator, so that it can be omitted in the national social welfare function (1).

3.2 The two stage game under the CETS

First stage: The centralized regulator chooses the levels of $\overline{e}_A$ and $\overline{e}_B$ required to maximize the aggregate social welfare:

$$W = \pi_A + \pi_B - c_A - c_B - D_A - D_B \tag{3}$$

where π_i is the expected gross profit of firm i $(i = A, B)$ that has been already defined in Sect. 3.1; $c_i = c_i(u_i)$ is the centralized regulator's cost of monitoring firm i, with $\frac{dc_i}{du_i} > 0$ and $\frac{d^2 c_i}{du_i^2} \geq 0$;[6] $D_i = D_i(e)$, is the damage from pollution to country i that has been already defined in Sect. 3.1.
Again, the levels of monitoring effort (u_A and u_B) are set in order to induce firm A and firm B to be fully compliant.
Second stage: It is exactly the same as in Sect. 3.1.

Finally, and obviously, also under the CETS the expected fine is a net transfer from the firms to the regulator. Then, it can be omitted also in the aggregate social welfare function (3).

3.3 The market of permits

In these games the equilibrium price of permits is implicitly defined by the following market clearing condition:[7]

$$q_A + q_B = \overline{e}_A + \overline{e}_B = \overline{e} \tag{4}$$

where the total amounts of permits held by the firms, on the left hand side, and total endowment of permits allocated to the firms, on the right hand side, represent the demand and the supply of permits respectively.

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[6] A more realistic setting would allow for the explicit introduction of centralized diseconomies of scale and for non separability in monitoring costs under centralization, implying an increasing and convex monitoring cost function depending on *total* monitoring effort (i.e. $c = c(u_i + u_j)$). Such an extension would, however, strengthen our results, as it would reinforce the consequences of monitoring cost advantages favoring decentralization.

[7] We limit our attention to the case of a strictly positive equilibrium permits price.

The demand side is defined by the conditions characterizing the optimal choices of the firms in the second stage of the game while the supply side is defined in the first stage of the game when the environmental regulators choose (at international or national level) the amount of emissions allowances to be issued to the two "representative" firms, taking into account how firms will react in the second stage. In so doing the regulators realize that the equilibrium price in the permits market can be influenced by their choice of $\overline{e}_i$ $(i = A, B)$, while firms face an exogenous price p because they do not have market power in the permits market.

4 The solutions of the games

In this section we solve the two games defined under the DETS and under the CETS in order to characterize the price of permits under the two alternative regulatory settings. To determine the subgame perfect equilibria of these games we proceed backward. Therefore, we solve first the firms' problem at the second stage of the game and then the regulator(s) problem at the first stage.

4.1 The firms' problem

By maximizing (2) we get the firms' first order conditions w.r.t. e_i

$$\frac{\partial B_i(e_i)}{\partial e_i} - \frac{\partial N(u_i, v_i)}{\partial v_i} = 0 \tag{5}$$

and w.r.t. q_i

$$-p + \frac{\partial N(u_i, v_i)}{\partial v_i} = 0. \tag{6}$$

In order to achieve full compliance, from conditions (5) and (6), the monitoring efforts must be such that the following condition holds:

$$p = \frac{\partial N(u_i^F, 0)}{\partial v_i} \tag{7}$$

that is, the marginal fine corresponding to full compliance effort (labeled as u_i^F) must be equal to the permits price.[8] The above condition implicitly defines $u_i^F(p)$. Of course, (7) implies that $u_A^F = u_B^F = u^F$. Further, differentiating (7) we get:

[8] Condition (7) is taken as a strict equality even if it is stronger than needed to ensure full compliance. We exclude the case of a marginal penalty larger than the equilibrium price at $v_i = 0$, as in the latter case, for any given p, a strict inequality would require more costly monitoring effort to achieve full enforcement. Also, given the assumptions $\frac{\partial N(u_i, v_i)}{\partial v_i} > 0$ and $N(u_i, 0) = 0$, we can conclude that for any $v_i > 0$ the marginal penalty will be larger than the permits price. It follows therefore that overall expected costs from violation exceed total benefits.

$$\frac{du^F}{dp} = \frac{1}{\frac{\partial^2 N(.)}{\partial v_i \partial u_i}} > 0.$$

Also, from (5) and (6) and from the fact that under full compliance $e_i = q_i,$ we get $\frac{\partial q_i}{\partial p} < 0$ for all i. Finally, totally differentiating (4) we obtain $\frac{dp}{d\bar{e}} = \frac{1}{\frac{\partial q_A}{\partial p} + \frac{\partial q_B}{\partial p}} < 0$, i.e. an increase in the initial endowment of permits in any country causes the equilibrium permits price to decrease. Combining the latter result with (7) we easily get the first result of our article:

Proposition 1 *An increase in allowances endowment decreases the effort needed in both countries to achieve full compliance, i.e.*

$$\frac{\partial u_i^F(p)}{\partial p}\frac{dp}{d\bar{e}} < 0$$

for any $i = A, B$.

In other words, the monitoring effort needed to achieve full compliance increases (decreases) with the equilibrium price of permits (the aggregate emission cap). This conclusion suggests the existence of a positive spillover between countries: an increase in the national cap in country i implies a decrease in permits price and, therefore, a decrease in the enforcement effort needed to achieve full compliance in country j. Although this result is not completely new in the literature,[9] its consequences are not yet fully investigated. The relevance of such spillover in a decentralized setting will be discussed in Sect. 5.

4.2 The regulators' problem under DETS

Regulator i defines the monitoring effort u_i^F required to achieve full compliance and the amount of allowances to be issued to domestic firms in order to maximize:

$$W_i = \pi_i - \psi_i(u^F) - D_i(e_i + e_j)$$

that is,

$$W_i = B_i(e_i) - p(e_i - \bar{e}_i) - \psi_i(u^F) - D_i(e_i + e_j) \tag{8}$$

Notice that, under the assumption of full compliance, the monitoring effort is uniquely determined by the price of permits and, therefore, by the initial allocation of permits. As a consequence, the only choice variables which are left to regulator(s) are

9 Murphy and Stranlund (2006) investigate the impact of a change in enforcement on the permits price, so that their paper is somewhat complementary to our analysis. Sigman (2010) suggests that a lower equilibrium price might imply a lower needed enforcement to guarantee full compliance. Also Silva and Zhu (2008) conclude that a lower equilibrium permit price resulting from a higher aggregate cap implies smaller inspection efforts in each region.

national emission targets. Therefore, taking the first order conditions with respect to $\overline{e}_i$, and imposing $\frac{\partial B_i(e_i)}{\partial e_i} = p$ from (5) and (6), we get:

$$\frac{\partial W_i}{\partial \overline{e}_i} = p - \frac{\partial p}{\partial \overline{e}_i}(e_i - \overline{e}_i) - \frac{\partial \psi_i(u^F)}{\partial u_i}\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}_i} - \left(\frac{\partial D_i}{\partial e_i}\frac{\partial e_i}{\partial p} + \frac{\partial D_i}{\partial e_j}\frac{\partial e_j}{\partial p}\right)\frac{\partial p}{\partial \overline{e}_i} = 0.$$

Since the equilibrium on the permits market implies $\left(\frac{\partial e_i}{\partial p} + \frac{\partial e_j}{\partial p}\right)\frac{\partial p}{\partial \overline{e}_i} = 1$ and the uniformly mixing pollutant assumption implies $\frac{\partial D_i}{\partial e_i} = \frac{\partial D_i}{\partial e_j}$, the above first order condition can be rewritten as:

$$\frac{\partial W_i}{\partial \overline{e}_i} = p - \frac{\partial p}{\partial \overline{e}_i}(e_i - \overline{e}_i) - \frac{\partial \psi_i(u^F)}{\partial u_i}\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}_i} - \frac{\partial D_i}{\partial e_i} = 0. \tag{9}$$

The corresponding first order condition for country j is, of course:

$$\frac{\partial W_j}{\partial \overline{e}_j} = p - \frac{\partial p}{\partial \overline{e}_j}(e_j - \overline{e}_j) - \frac{\partial \psi_j(u^F)}{\partial u_j}\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}_j} - \frac{\partial D_j}{\partial e_j} = 0. \tag{10}$$

Solving (9) with respect to $\frac{\partial p}{\partial \overline{e}_i}(e_i - \overline{e}_i)$, taking into account that the equilibrium on the permits market implies $\frac{\partial p}{\partial \overline{e}_i}(e_i - \overline{e}_i) = -\frac{\partial p}{\partial \overline{e}_j}(e_j - \overline{e}_j)$ and substituting in (10) we get, after some manipulation, the following condition for the equilibrium price of permits under decentralization, labelled as p_d:

$$p_d = \frac{1}{2}\left(\frac{\partial \psi_i(u^F(\overline{e}_d))}{\partial u_i} + \frac{\partial \psi_j(u^F(\overline{e}_d))}{\partial u_j}\right)\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}_d} + \frac{1}{2}\left(\frac{\partial D_i}{\partial e_i} + \frac{\partial D_j}{\partial e_i}\right) \tag{11}$$

where $\overline{e}_d$ is the aggregate equilibrium cap set under this institutional setting.

4.3 The regulator's problem under CETS

The centralized regulator chooses emission allowances to be allocated to the firms in the two countries in order to achieve full compliance and to maximize (3). Under the CETS we can consider any permits revenue (cost) of firm i $(i = A, B)$ as an equivalent cost (revenue) of firm j $(j = A, B, j \neq i)$. Therefore we can rewrite (3) as follows:

$$W = B_A(e_A) + B_B(e_B) - c_A(u^F) - c_B(u^F) - D_A(e_A + e_B) - D_B(e_A + e_B) \tag{12}$$

By taking the first derivative of (12) with respect to $\overline{e}_i (i = A, B)$ and using the same arguments as in Sect. 4.2, we get:

$$\frac{\partial W}{\partial \overline{e}_i} = p - \frac{\partial c_i(u^F)}{\partial u_i}\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}_i} - \frac{\partial c_j(u^F)}{\partial u_j}\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}_i} - \frac{\partial D_i}{\partial e_i} - \frac{\partial D_j}{\partial e_i} = 0 \tag{13}$$

By rearranging (13) we finally get the equilibrium price of permits under the CETS, labelled as p_c:

$$p_c = \left(\frac{\partial c_i(u^F(\overline{e}_c))}{\partial u_i} + \frac{\partial c_j(u^F(\overline{e}_c))}{\partial u_j} \right) \frac{\partial u^F}{\partial p} \frac{\partial p}{\partial \overline{e}_c} + \frac{\partial D_i}{\partial e_i} + \frac{\partial D_j}{\partial e_i} \tag{14}$$

where $\overline{e}_c$ is the aggregate equilibrium cap arising under this institutional setting.

Notice that, since the assumption of full compliance implies that the monitoring effort is uniquely determined by the price of permits and, therefore, by the initial allocation of permits, the first order conditions derived under the centralized analysis can be useful to investigate also a system where the choice of monitoring effort is taken by decentralized countries while the overall emissions target is set by a centralized regulator.[10]

5 Environmental quality and social welfare

Any increase in permits endowments in one country causes a number of conflicting effects on the other country that a decentralized regulator would not internalize or account for. Moreover, the effect of an increase in permits endowments on the enforcement cost of a decentralized regulator could be different from that on the enforcement cost of a centralized regulator. To identify all these effects we compare the first derivatives of W and W_i with respect to $\overline{e}_i$, for given levels of $\overline{e}_i$ and $\overline{e}_j$:

$$\frac{\partial W}{\partial \overline{e}_i} - \frac{\partial W_i}{\partial \overline{e}_i} = \left(\frac{\partial \psi_i(u^F)}{\partial u_i} - \frac{\partial c_i(u^F)}{\partial u_i} \right) \frac{\partial u^F}{\partial p} \frac{\partial p}{\partial \overline{e}_i} - \frac{\partial c_j(u^F)}{\partial u_j} \frac{\partial u^F}{\partial p} \frac{\partial p}{\partial \overline{e}_i}$$
$$- \frac{\partial D_j}{\partial e_i} - \frac{\partial p}{\partial \overline{e}_i}(e_j - \overline{e}_j)$$

The term $-\frac{\partial p}{\partial \overline{e}_i}(e_j - \overline{e}_j)$ is due to the fact that an increase in the initial allocation of permits in country i also decreases the equilibrium permits price. If country j's "representative" firm is a net seller of permits, this will cause a negative spillover on country j's welfare. If the "representative" firm operating in country j is a net buyer of permits, this spillover will be positive. The overall effect between the two countries cancels out, however, because, when the permits market is in equilibrium, the positive spillover in one country perfectly offsets the negative spillover in the other. Such spillover is therefore likely to have only distributional consequences. We label such spillover as *distributional spillover*.

The term $-\frac{\partial D_j}{\partial e_i}$ captures a second spillover: this is an international externality that the choice of the environmental authority of country i causes to country j. As we know, an increase in permits by any country leads to an increase in emissions that will also damage the other country. However, it is worthwhile to note that this externality

[10] Such a system is compatible with the provisions of Directive 2009/29/CE, concerning the EU ETS after 2013.

is a non standard result, as it is a consequence of the permits market per se, and it does not only depend on the global nature of the environmental issue we are dealing with. As a matter of fact, even if the environmental damages of the two countries depended only on the emissions generated within their borders, an increase in $\overline{e}_i$ would still bring about more emissions in country j via the induced reduction in p. This effect is discussed in detail by D'Amato and Valentini (2009). In the rest of the article we will label such international environmental externality as a *pollution spillover*.

The term $-\frac{\partial c_j(u^F)}{\partial u_j}\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}_i}$ identifies a positive spillover between countries, already explained in Proposition 1: an increase in permits endowment in country i leads to a decrease in equilibrium permits price and, therefore, to a decrease in the amount of monitoring effort needed to achieve full compliance, leading to a reduction in related costs. We call such spillover *enforcement spillover*.

Finally, the term $\left(\frac{\partial \psi_i(u^F)}{\partial u_i}-\frac{\partial c_i(u^F)}{\partial u_i}\right)\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}_i}$ identifies the consequences of any asymmetry in enforcement costs between centralized and decentralized institutional scenarios. We label the related impact, that will be addressed in the last part of this section, as *monitoring cost effect*. Of course, this term disappears if no cost differential is assumed between centralized and decentralized regulators.

The net impact of the three spillovers, coupled with the effect of monitoring cost differentials, is not obvious or straightforward. To gain further insights, firstly we restrict the analysis to a symmetric setting which allows to investigate all the consequences of decentralization per se, that is those consequences not depending on asymmetries between countries or between the monitoring costs of the decentralized and the centralized regulators. Then we remove the assumption of symmetry across institutional settings in order to look into the consequences of asymmetries in monitoring costs.

5.1 Symmetry between countries and institutional settings

Assume that countries are symmetric. This amounts to assuming that, $c_i(.) = c(.)$ under the CETS, $\psi_i(.) = \psi(.)$ under the DETS, $D_i(.) = D(.)$ and $B_i(.) = B(.)$ for $i = A, B$. As a consequence, we can rewrite conditions (14) and (11) as:

$$p_c = 2\frac{\partial c(u^F)}{\partial u_i}\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}} + 2\frac{\partial D}{\partial e_i} \tag{15}$$

$$p_d = \frac{\partial \psi(u^F)}{\partial u_i}\frac{\partial u^F}{\partial p}\frac{\partial p}{\partial \overline{e}} + \frac{\partial D}{\partial e_i} \tag{16}$$

Then, the following result is straightforward.

Proposition 2 *If no asymmetry is introduced between countries, then the positive enforcement spillover is always dominated by the negative pollution spillover.*

Proof The result follows immediately from either (15) or (16) and the assumption of a strictly positive permits price. □

Moreover, if no cost advantage is assumed in favor of the decentralized regulators, it must be that $c(.) = \psi(.)$. We get therefore the following:

Proposition 3 *If no asymmetry is introduced between countries and institutional settings, decentralization per se always leads to higher emissions and a lower permits price than centralization. The corresponding effort to achieve full compliance is smaller under a DETS.*

Proof Given our additional symmetry assumptions, we can rewrite the first order conditions for the centralized and decentralized case, respectively, as follows:

$$\frac{\partial B(.)}{\partial e_i} - \frac{\partial c(u^F(\overline{e}_c))}{\partial u}\frac{\partial u^F(\overline{e}_c)}{\partial p}\frac{\partial p(\overline{e}_c)}{\partial \overline{e}} - \frac{\partial D(\overline{e}_c)}{\partial e_i} = \frac{\partial D(\overline{e}_c)}{\partial e_i} + \frac{\partial c(u^F(\overline{e}_c))}{\partial u}\frac{\partial u^F(\overline{e}_c)}{\partial p}\frac{\partial p(\overline{e}_c)}{\partial \overline{e}_i} \quad (17)$$

$$\frac{\partial B(.)}{\partial e_i} - \frac{\partial c(u^F(\overline{e}_d))}{\partial u_i}\frac{\partial u^F(\overline{e}_d)}{\partial p}\frac{\partial p(\overline{e}_d)}{\partial \overline{e}_i} - \frac{\partial D(\overline{e}_d)}{\partial e_i} = 0 \quad (18)$$

where the right hand side in (17) is strictly positive by Proposition 2, while in (18) we accounted for the fact that under perfect symmetry there is no trading of permits in equilibrium. As the left hand side of both (17) and (18) must be decreasing in $\overline{e}_i$ to ensure that the decentralized regulators problems are concave problems, and as, from (7), $\frac{\partial u^F}{\partial p} > 0$, the proof is completed. □

The last two results have relevant consequences on the choice between the CETS and the DETS. More specifically, in a perfectly symmetric framework, the choice of a decentralized setting can be supported neither in terms of social welfare (which is of course higher *by definition* in a centralized setting) nor under an environmental quality point of view. Further, Proposition 2 implies that, unless the permits price is driven to 0, full compliance does not alter the presence of an "aggregate" negative spillover between symmetric countries in a decentralized setting.

5.2 Asymmetry between institutional settings

The symmetric setting is useful as a benchmark. As we demonstrated, when countries are completely identical and there is no monitoring cost advantage favoring the DETS, the latter cannot be justified under any respect. A question which is left open is, however, why did the European Commission choose decentralization in the first place? As already outlined in the introduction, the answer to this question might depend on the relative ease in monitoring and enforcement that might characterize local regulators. In order to get tractable insights we need, however, to keep the symmetric countries assumption and to introduce specific functional forms for costs, benefits and social welfare functions. We rely on a quadratic specification that might be somewhat limiting in terms of the generality of results. This is however, in our view, a cost which is worth paying, as our simplified setting allows us to get results which are, at the same time, new to the existing literature and potentially relevant for their policy implications.

5.2.1 Model results

We assume for country i ($i = A, B$) the following specific shapes for the benefits and expected fine functions:

$$B(e_i) = e_i - \frac{e_i^2}{2}$$

and

$$N(u_i, v_i) = \begin{cases} u_i \left(F(e_i - q_i) + \frac{1}{2}(e_i - q_i)^2 \right) & \text{for } e_i > q_i \\ 0 & \text{otherwise} \end{cases}$$

where F is a positive constant representing the unit fine for noncompliance.

The damage function for each country is quadratic and implies (coherently with the assumption of symmetry between countries) that marginal damage is the same in country A and B for any given amount of total emissions:

$$D(.) = \frac{1}{2}(\overline{e}_A + \overline{e}_B)^2$$

Finally, the monitoring cost function is assumed to be linear in monitoring effort, and is the only source of asymmetry between the institutional settings.[11] More specifically, under the CETS:

$$c(.) = \lambda_c u,$$

while under the DETS:

$$\psi(.) = \lambda_d u.$$

Using the above functional forms and solving firms' and regulators' maximization problems we get the following values for aggregate environmental targets, equilibrium price of permits, monitoring needed to achieve full compliance and social welfare (notice that, as before, subscripts c label values obtained in a centralized setting, while d labels decentralization results):[12]

[11] It is, again, crucial to underline that introducing centralized diseconomies of scale, in the spirit of Butler and Macey (1996), would simply reinforce our results.

[12] We do not go into the details of the numerical calculations, that are coherent with the implicit calculations performed in the preceeding sections. All the details are available from the authors upon request. Further, in order to guarantee that price of permits is not driven to 0, we must assume that *max* $\{\lambda_c, \lambda_d\} < 4F$.

	Centralized	Decentralized
Emissions	$\overline{e}_c = \frac{1}{5F}(2F + 2\lambda_c)$	$\overline{e}_d = \frac{1}{3F}(2F + \lambda_d)$
Price	$p_c = \frac{1}{5F}(4F - \lambda_c)$	$p_d = \frac{1}{6F}(4F - \lambda_d)$
Monitoring	$u_c = \frac{1}{5F^2}(4F - \lambda_c)$	$u_d = \frac{1}{6F^2}(4F - \lambda_d)$
Welfare	$W_c = \frac{1}{5F^2}\left(F^2 - 8F\lambda_c + \lambda_c^2\right)$	$W_d = \frac{1}{36F^2}\left(4F^2 - 56F\lambda_d + 7\lambda_d^2\right)$

5.2.2 Comparisons

In order to make comparisons easier, we assume the following relationship between centralized and decentralized monitoring costs:

$$\lambda_c = \eta\lambda_d;$$

as a consequence, when $\eta \in (0, 1)$ monitoring is more costly under decentralization, while when $\eta \in (1, \infty)$ there is a cost advantage in favor of decentralized regulators.

The comparison of aggregate caps arising under CETS and under DETS leads to the following result:

$$\Delta\overline{e} = \overline{e}_d - \overline{e}_c = \frac{1}{15F}(5\lambda_d + 4F - 6\lambda_d\eta) \tag{19}$$

which is negative, implying a higher cap in the centralized case, if

$$\eta > \frac{1}{6\lambda_d}(4F + 5\lambda_d) = \eta_e$$

where it is easily shown that $\eta_e > 1$.

We can therefore state the following Proposition:

Proposition 4 *A sufficiently high cost differential in favor of the decentralized regulators leads the aggregate cap to be higher under centralization. More specifically, in our modeling framework, we get the following two cases:*

$$\begin{cases} \textit{if} \;\; 0 < \eta < \eta_e & \textit{then} \;\; \Delta\overline{e} > 0 \\ \textit{if} \;\; \eta > \eta_e & \textit{then} \;\; \Delta\overline{e} < 0 \end{cases}$$

The intuition for this result is as follows; only when the cost differential in favor of decentralized regulators is sufficiently high, then the "differential" incentive of the centralized regulator to decrease permits price to achieve full compliance with lower monitoring effort is so strong to counterbalance any negative spillover between countries related to emissions. In fact, when the cost differential is relatively small, the opposite happens.

Turning to welfare comparison we get:

$$\Delta W = W_d - W_c = \frac{1}{180}\frac{35\lambda_d^2 + 288\eta\lambda_d F - 16F^2 - 280F\lambda_d - 36\eta^2\lambda_d^2}{F^2}. \tag{20}$$

Introduce the following notation: $\eta_W^1 = \frac{1}{6}\frac{24F - \sqrt{35}(4F-\lambda_d)}{\lambda_d}$; $\eta_W^2 = \frac{1}{6}\frac{24F + \sqrt{35}(4F-\lambda_d)}{\lambda_d}$. It is easily shown that $\eta_W^2 > \eta_e > \eta_W^1 > 1$ and that $\eta_W^2 > \frac{4F}{\lambda_d}$. As a consequence, we can never have the case that $\eta > \eta_W^2$ as it would imply a null (decentralized) equilibrium permits price.

This leads us to the following Proposition.

Proposition 5 *When CETS monitoring costs are sufficiently high relative to DETS, DETS results in a higher social welfare. More specifically*

$$\begin{cases} \text{if } \eta < \eta_W^1 & \text{then } \Delta W < 0 \\ \text{if } \eta_W^1 < \eta < \frac{4F}{\lambda_d} & \text{then } \Delta W > 0 \end{cases}$$

Results in propositions 4 and 5 can be summed up in three possible cases:

1. $\Delta W < 0$ and $\Delta \bar{e} > 0$ for $\eta < \eta_W^1$
   In this case the cost differential is sufficiently low to keep emissions higher in a decentralized setting. A cost advantage under decentralization is not enough to counterbalance the related environmental damage in terms of social welfare.
2. $\Delta W > 0$ and $\Delta \bar{e} > 0$ for $\eta_W^1 < \eta < \eta_e$
   In this case emissions are higher in a decentralized setting, but decentralization also features a higher welfare. This could be the case because the cost differential is now higher in favor of a decentralized setting.
3. $\Delta W > 0$ and $\Delta \bar{e} < 0$ for $\eta_e < \eta < \frac{4F}{\lambda_d}$
   In this third case emissions are larger under centralization. This is the most favorable case for the DETS.

Notice, further, that λ_d plays an important role in determining all the above threshold values. Taking the first derivative of η_e and η_W^1 with respect to λ_d we get:

$$\frac{\partial \eta_e}{\partial \lambda_d} = -\frac{2F}{3\lambda_d^2} < 0$$

$$\frac{\partial \eta_W^1}{\partial \lambda_d} = \left(\frac{2}{3}\sqrt{35} - 4\right)\frac{F}{\lambda_d^2} < 0$$

As a consequence, an increase in λ_d reduces the threshold above which emissions are higher in a centralized setting as well as the threshold above which social welfare is higher in a decentralized setting.

Results obtained are coherent and add to those gained in Sect. 4. A number of lessons can be learned from our analysis: first of all, if no asymmetry between countries and/or institutional settings is introduced, decentralization cannot be justified under any respect (social welfare and/or environmental quality); second, the introduction of a monitoring cost differential in favor of decentralized regulators is a necessary but not sufficient condition to provide support to a DETS. Decentralization is only justifiable if such cost differential is sufficiently high as to provide the centralized regulator with relatively strong incentives to issue permits in order to drive the price (as well as the monitoring effort) down. Finally, an increase in decentralized (and, given η, centralized) unit monitoring costs implies all the thresholds defined above to shift down, leading to an even less favorable situation for centralization. This is reasonable: when $\eta > 1$ the incentive for the centralized regulator to issue permits in order to drive full compliance monitoring down grows more rapidly than the same incentive in a decentralized setting.

All the above results might be a theoretical base in support of the choice of the European Commission to choose a centralized framework in issuing allowances while keeping decentralized monitoring. Indeed, such setting gets the best out of the ETS. Consider a "mixed" case where the total cap is set by a unique regulator but, as monitoring is decentralized, unit costs are given by λ_d. We are therefore in a CETS with unit monitoring costs corresponding to those under decentralized regulation. From (19) and (20) we can easily conclude, respectively, that:

$$\Delta \overline{e} = \overline{e}_d - \overline{e}_m = \frac{1}{15} \frac{4F - \lambda_d}{F} > 0$$

and

$$\Delta W = W_d - W_m = -\frac{1}{180} \frac{(4F - \lambda_d)^2}{F^2} < 0.$$

where $\overline{e}_m = \frac{1}{5F}(2F + 2\lambda_d)$, $W_m = \frac{1}{5F^2}\left(F^2 - 8F\lambda_d + \lambda_d^2\right)$ and the subscript m labels the values obtaind under the "mixed" institutional setting. It is also easily shown that the "mixed system", where monitoring is decentralized, dominates the fully centralized framework when the latter features larger unit monitoring costs. Therefore, our article might provide a rationale for decentralizing monitoring (when such choice implies lower enforcement costs) while keeping the decision on emission caps at a centralized level.

6 Concluding remarks

In this article, we have addressed the consequences of decentralizing compliance monitoring and permits allocation under international emissions trading. Using a two stage game played by two regulators, and their respective polluting industries, we identified various spillovers between countries arising under decentralization and assessed the desirability of decentralization itself under different assumptions concerning monitornig costs.

Further steps for improving the study presented in this article could be the extension of welfare analysis to a more general setting where no explicit functional form is introduced, the removal of both the symmetry assumptions between countries and the full compliance assumption, the explicit modeling of the output market. Despite of these limits, by simply introducing the possibility of monitoring cost differentials between national environmental authorities and a centralized one operating at international level we have been able to show that decentralization is not necessarily an inefficient policy choice. Indeed, a significant monitoring cost advantage in favor of decentralized authorities might imply lower emissions and greater welfare under a

DETS than under a CETS. This result is particularly relevant since it allows to find an economic justification for decentralization which is based on efficiency and not on other political arguments as in D'Amato and Valentini (2009).

We have also shown, however, that the comparison is by no means straightforward: a cost advantage in favor of national states is not sufficient to justify decentralization, as it interacts in a complex way with spillovers between countries arising in a decentralized setting. As a consequence, the extent of possible cost differentials (if any) should be carefully evaluated in order to express any definitive judgement on the two alternative emission trading regimes.

Finally, our conclusions also provide support for the choice of the EU Commission to adopt, after 2013, a "mixed" emissions trading system, where monitoring is decentralized but the cap is set at the EU level. Indeed, under the reasonable assumption that monitoring is easier for decentralized governments, the "new" EU ETS, introduced by Directive 2009/29/CE, is capable to outperform a fully decentralized and a fully centralized ETS both in terms of environmental quality and in terms of aggregate social welfare, as it takes out the best of the two institutional settings.

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