Online Appendix

Transboundary Natural Resources, Externalities, and Firm Preferences for Regulation

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Appendix A: Resource Management under Trade

In this section, we extend the analysis of regulation of transboundary natural resources to incorporate trade between the countries sharing the resource. In particular, we analyze a two-country trade union model (Duval and Hamilton, 2002), where firms in each of two countries now compete for consumers located in both countries.

In the spirit of Brander and Spencer (1985), Conrad (1993), Barrett (1994), Kennedy (1994), and Ulph (1996), we allow for firms in each country to produce a non-differentiated product, where production costs and the number of firms across countries can still vary. The final product is traded between the two countries without transportation costs. We model domestic consumption within each region according to Duval and Hamilton (2002). Consumers in both countries have homogeneous preferences, but the size of each market can differ. Specifically, if CS represents consumer surplus from global demand, consumer surplus in country i is captured by $CS^i = \alpha^i CS$, where α^i is country i's share of global consumer surplus, for and $\alpha^i + \alpha^l = 1$. Given homogeneous consumers and the absence of transportation costs between countries, it follows that a single market price prevails, i.e., $p = a - Q$, where $Q = Q^i + Q^l$.

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A.1 Industry Equilibrium

In the second stage, firm j in country i takes the environmental policy (τ^i) as given and solves

$$\max_{q_j^i \geq 0} \quad \pi_j^i = \left(a - q_j^i - Q_{-j}^i - Q^l\right) q_j^i - \left(c^i + \tau^i\right) q_j^i, \tag{1}$$

where $Q_{-j}^i = \sum_{k \neq j} q_k^i$. In Lemma A.1, we present firm's best response function and the corresponding equilibrium output and profits.

Lemma A.1. *Firm j's best response function is* $q_j^i(Q_{-j}^i, Q^l, \tau^i) = \frac{a-(c^i+\tau^i)}{2} - \frac{1}{2}Q_{-j}^i - \frac{1}{2}Q^l$, *with equilibrium output and profits of* $q_j^i(\tau^i, \tau^l) = \frac{a-c^i-\tau^i-n^l(c^i+\tau^i)+n^l(c^l+\tau^l)}{n^i+n^l+1}$ *and* $\pi_j^i(\tau^i, \tau^l) = \left(\frac{a-c^i-\tau^i-n^l(c^i+\tau^i)+n^l(c^l+\tau^l)}{n^i+n^l+1}\right)^2$, *respectively.*

It is straightforward to show that $\frac{\partial q_j^i(\tau^i,\tau^l)}{\partial \tau^i} = -\frac{n^l+1}{n^i+n^l+1} < 0$ and $\frac{\partial q_j^i(\tau^i,\tau^l)}{\partial \tau^l} = \frac{n^l}{n^i+n^l+1} > 0$. In other words, an increase in domestic environmental tax will reduce the equilibrium output of the domestic producers and raise the output of the foreign rivals, other things being equal.

A.2 The Planning Problem

We next analyze the social planner's problem in the first stage of the game under three different regulatory settings. We start with the case where there is no regulation to control the appropriation of the CPR.

Lemma A.2. *In the absence of environmental regulation, firm j in country i produces* $q_j^{i,U} = \frac{a-(1+n^l)c^i+n^lc^l}{n^i+n^l+1}$, *earning profits of* $\pi_j^{i,U} = \left(\frac{a-(1+n^l)c^i+n^lc^l}{n^i+n^l+1}\right)^2$, *which yields aggregate output of* $Q^U = Q^{i,U} + Q^{l,U} = \frac{n^i(a-c^i)+n^l(a-c^l)}{n^i+n^l+1}$.

Let us next examine industry production and profits corresponding to non-cooperative setting. The objective function of a national regulator remains the same as in equation (4), except for the producer surplus, which is obtained using equation (11), and consumer surplus, which is now expressed as $CS^i = \alpha^i CS = \frac{\alpha^i}{2}\left(q_j^i + Q_{-j}^i + Q^l\right)^2$.

Proposition A.1. *Under non-cooperative (NC) regulation, every country i sets*

$$\tau^{i,NC} = \frac{z^i(n^i+n^l)(1+d^i)}{n^i(n^i+n^l)} - \frac{n^i(a-c^i) - z^i(1+d^i) + n^l(a-c^l) - z^l(1+d^l)}{n^i(n^i+n^l)}\alpha^i, \tag{2}$$

which yields an equilibrium output of

$$\begin{aligned} q_j^{i,NC} \quad = \quad & \frac{n^i n^l(c^l-c^i) - n^l z^i(1+d^i) + n^i z^l(1+d^l)}{n^i(n^i+n^l)} + \\ & \frac{n^i(a-c^i) - z^i(1+d^i) + n^l(a-c^l) - z^l(1+d^l)}{n^i(n^i+n^l)}\alpha^i \end{aligned} \tag{3}$$

for every firm j.

Similar to autarky, environmental tax $\tau^{i,NC}$ increases in both the appropriation rate z^i and the damage parameter d^i, $\frac{\partial \tau^{i,NC}}{\partial z^i} = \frac{(n^i+n^l+\alpha^i)(1+d^i)}{n^i(n^i+n^l)} > 0$ and $\frac{\partial \tau^{i,NC}}{\partial d^i} = \frac{(n^i+n^l+\alpha^i)z^i}{n^i(n^i+n^l)} > 0$, respectively, while the individual firm's equilibrium output $q_j^{i,NC}$ decreases in these two parameters, $\frac{\partial q^{i,NC}}{\partial z^i} = -\frac{(n^l+\alpha^i)(1+d^i)}{n^i(n^i+n^l)} < 0$ and $\frac{\partial q^{i,NC}}{\partial d^i} = -\frac{(n^l+\alpha^i)z^i}{n^i(n^i+n^l)} < 0$. In addition, with international trade, the domestic (non-cooperative) environmental regulation and production decisions become sensitive to foreign appropriation rate of the commons and the extent of environmental damage. Specifically, both $\tau^{i,NC}$ and $q_j^{i,NC}$ increase in both z^l and d^l: $\frac{\partial \tau^{i,NC}}{\partial z^l} = \frac{\alpha^i(1+d^l)}{n^i(n^i+n^l)} > 0$, $\frac{\partial \tau^{i,NC}}{\partial d^l} = \frac{\alpha^i z^l}{n^i(n^i+n^l)} > 0$, $\frac{\partial q^{i,NC}}{\partial z^l} = \frac{(n^i-\alpha^i)(1+d^l)}{n^i(n^i+n^l)} > 0$, and $\frac{\partial q^{i,NC}}{\partial d^l} = \frac{(n^i-\alpha^i)z^l}{n^i(n^i+n^l)} > 0$. Intuitively, when the foreign production becomes more intensive in the use of the natural resource, or the extraction of the resource entails larger environmental damage, then the foreign regulator imposes more stringent environmental policy on its industries (since $\frac{\partial \tau^{l,NC}}{\partial z^l} > 0$ and $\frac{\partial \tau^{l,NC}}{\partial d^l} > 0$), which in turn reduces the market share of foreign firms. The domestic firms' reaction in this situation is to increase production to capture larger market share (hence $\frac{\partial q^{i,NC}}{\partial z^l} > 0$ and $\frac{\partial q^{i,NC}}{\partial d^l} > 0$). With increased production, however, the pressure on the stock of the commons and the environment increases, thus forcing the domestic regulator to tighten the environmental policy (thus $\frac{\partial \tau^{i,NC}}{\partial z^l} > 0$ and $\frac{\partial \tau^{i,NC}}{\partial d^l} > 0$).

Furthermore, when the sum of marginal social costs of resource extraction in two countries is sufficiently low, i.e., $z^i(1+d^i)+z^l(1+d^l) < n^i(a-c^i)+n^l(a-c^l)$, an increase in the share of domestic consumer surplus (α^i) leads to a decrease in the environmental tax and an increase in domestic equilibrium production.

When environmental decisions are made at the global level, the problem is equivalent to one in which countries cooperatively determine environmental policies to maximize joint welfare, as characterized by following proposition.

Proposition A.2. *Under cooperative (C) regulation, the joint welfare maximum is characterized as follows:*

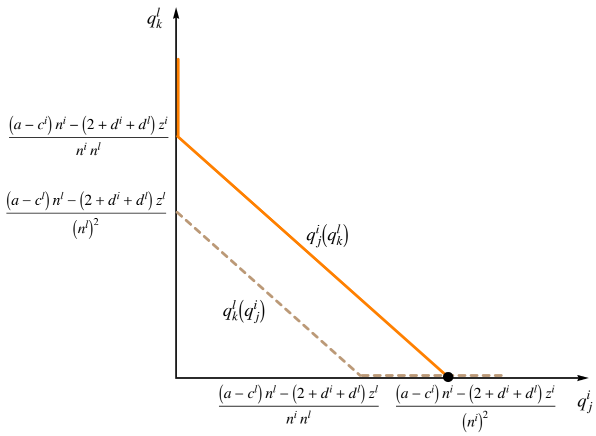
- *Scenario 1: $z^i < \bar{\bar{z}}$: Country i sets $\tau^{i,C} = \frac{z^i(n^i+1)(2+d^i+d^l)-n^i(a^i-c^i)}{(n^i)^2}$ which yields an equilibrium output of $q_j^{i,C} = \frac{n^i(a^i-c^i)-z^i(2+d^i+d^l)}{(n^i)^2}$ for every firm j; while country l sets $\tau^{l,C} = \frac{z^i(2+d^i+d^l)}{n^i} - c^l + c^i$ which yields an equilibrium output of $q_k^{l,C} = 0$ for every firm k;*

- *Scenario 2: $z^i > \bar{\bar{z}}$: Country i sets $\tau^{i,C} = \frac{z^l(2+d^i+d^l)}{n^l} - c^i + c^l$ which yields an equilibrium output of $q_j^{i,C} = 0$ for every firm j; while country l sets $\tau^{l,C} = \frac{z^l(n^l+1)(2+d^i+d^l)-n^l(a^l-c^l)}{(n^l)^2}$ which yields an equilibrium output of $q_k^{l,C} = \frac{n^l(a^l-c^l)-z^l(2+d^i+d^l)}{(n^l)^2}$ for every firm k;*

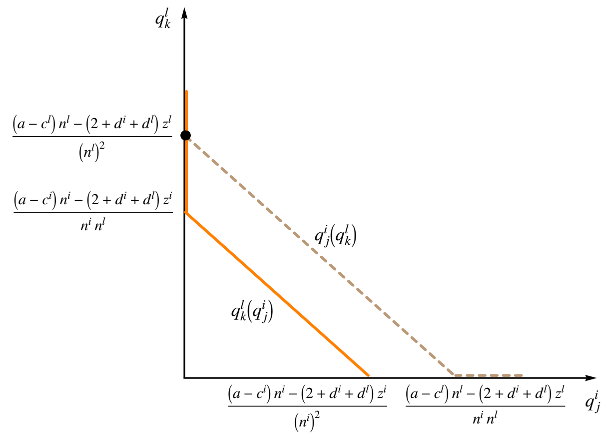
- *Scenario 3: $z^i = \bar{\bar{z}}$: Any combination of (q_j^i, q_k^l)-pairs satisfying $q_j^i = \frac{n^i(a^i-c^i)-z^i(2+d^i+d^l)}{(n^i)^2} - \frac{n^l}{n^i}q_k^l$ are socially optimal,*

where $\bar{\bar{z}} = \frac{n^i(c^l-c^i)}{2+d^i+d^l} + \frac{n^i}{n^l}z^l$.

As depicted in Figure A.1, when the appropriation rate in country i is relatively low ($z^i < \bar{\bar{z}}$), it is optimal if entire production takes place in country i, whilst that in country l shuts down. Conversely, if country i's production is relatively resource-intensive ($z^i > \bar{\bar{z}}$), then it is socially efficient to move entire production to country l. Lastly, if the extraction rates in two countries are relatively symmetric, then it is welfare maximizing to split the production between the two countries.



(a) Scenario 1: $z^i < \bar{\bar{z}}$



(b) Scenario 2: $z^i > \bar{\bar{z}}$

Figure A.1: Socially optimal cooperative firm output levels

A.3 Profit Comparison

Proposition A.3. *Firm's equilibrium profits under non-cooperative regulation are larger than under no regulation,* $\pi_j^{i,NC} > \pi_j^{i,U}$*, if and only if:*

- $z^i < \bar{z}_6$ *or* $z^i > \bar{z}_7$ *for* $c^i < \frac{a+c^l n^l}{1+n^l}$*;*
- $z^i < \bar{z}_7$ *or* $z^i > \bar{z}_6$ *for* $c^i > \frac{a+c^l n^l}{1+n^l}$*,*

where

$$\bar{z}_6 \equiv \frac{[n^i(a-c^i)+n^l(a-c^l)][(1+n^i+n^l)\alpha^i-n^i]}{(1+d^i)(1+n^i+n^l)(n^l+\alpha^i)} + \frac{(1+d^l)(n^i-\alpha^i)}{(1+d^i)(n^l+\alpha^i)}z^l \tag{4}$$

$$\bar{z}_7 \equiv \frac{[n^i(a-c^i)+n^l(a-c^l)][(1+n^i+n^l)\alpha^i+n^i]}{(1+d^i)(1+n^i+n^l)(n^l+\alpha^i)} + \frac{2n^i n^l(c^l-c^i)}{(1+d^i)(n^l+\alpha^i)} + \frac{(1+d^l)(n^i-\alpha^i)}{(1+d^i)(n^l+\alpha^i)}z^l \tag{5}$$

The explanation and intuition for profit ranking in different regions identified by above cutoffs remain the same as in the autarky, with only change being in the relative positions of the cutoffs. Therefore, we refer the reader to the paragraph following Proposition 3 for further details.

For the analysis of cooperative profits, we consider the case where $z^i < \bar{\bar{z}}$ (i.e., Scenario 1 in Proposition A.2), and thus only firms in country i produce positive amount, whilst those in country l remain inactive.

Proposition A.4. *Firm's equilibrium profits under cooperative regulation are larger than under no regulation,* $\pi_j^{i,C} > \pi_j^{i,U}$*, if and only if:*

- $z^i < \bar{\bar{z}}$ *for* $c^i < \frac{a+c^l n^l}{1+n^l}$ *and* $d^i + d^l < \bar{D}_1$*;*
- $z^i < \bar{z}_8$ *for* $c^i < \frac{a+c^l n^l}{1+n^l}$ *and* $d^i + d^l \in (\bar{D}_1, \bar{D}_2)$*;*
- $z^i < \bar{z}_8$ *or* $z^i \in (\bar{z}_9, \bar{\bar{z}})$ *for* $c^i < \frac{a+c^l n^l}{1+n^l}$ *and* $d^i + d^l > \bar{D}_2$*;*
- $z^i < \bar{\bar{z}}$ *for* $c^i > \frac{a+c^l n^l}{1+n^l}$ *and* $d^i + d^l < \bar{D}_2$*;*
- $z^i < \bar{z}_9$ *for* $c^i > \frac{a+c^l n^l}{1+n^l}$ *and* $d^i + d^l \in (\bar{D}_2, \bar{D}_1)$*;*
- $z^i < \bar{z}_9$ *or* $z^i \in (\bar{z}_8, \bar{\bar{z}})$ *for* $c^i > \frac{a+c^l n^l}{1+n^l}$ *and* $d^i + d^l > \bar{D}_1$*,*

where

$$\bar{D}_1 \equiv \frac{[a + c^i n^i - c^l(1+n^i)](1+n^l)n^l}{(n^i + n^l + 1)z^l} - 2, \tag{6}$$

$$\bar{D}_2 \equiv \frac{[a - c^i n^i - c^l(1+n^i)](1+n^l)n^l + (a - n^l c^l)2n^i n^l}{(n^i + n^l + 1)z^l} - 2, \tag{7}$$

$$\bar{z}_8 \equiv \frac{n^i[(a-c^i)(1+n^l) + n^i n^l(c^i - c^l)]}{(n^i + n^l + 1)(2 + d^i + d^l)}, \tag{8}$$

$$\bar{z}_9 \equiv \frac{n^i[(a-c^i)(1+n^l+2n^i) - n^i n^l(c^i - c^l)]}{(n^i + n^l + 1)(2 + d^i + d^l)}. \tag{9}$$

The intuitive explanation for profit ranking in different regions identified by above cutoffs remain the same as in the autarky, with only change being in the relative positions of the cutoffs. Hence, the reader is referred to the paragraph following Proposition 4 for detailed description.

Appendix B: Deviation from Cooperative Outcome

In this appendix, we explore a country's incentives to deviate from the cooperative outcome (policy coordination across countries). In particular, we consider the case where country l

chooses to cooperate, while country i contemplates defection given the cooperative outcome selected by country l.

Country l that chooses to cooperate solves

$$\max_{\{q_j^l\}_{j=1}^{n^l}} SW = SW^i + SW^l$$

where SW^i and SW^l are defined as in equation (4). Solving the social planner's problem yields the optimal output of $q_j^{l,C} = \frac{n^l(a^l - c^l) - z^l(2 + d^l + d^i)}{(n^l)^2}$ with the associated emission fees of $\tau^{l,C} = \frac{z^l(n^l+1)(2+d^l+d^i) - n^l(a^l - c^l)}{(n^l)^2}$. In contrast, country i chooses to defect (due to private incentives), given the cooperative output level chosen by country i, and solves

$$\max_{\{q_j^i\}_{j=1}^{n^i}} SW^i \quad = \quad PS^i + CS^i + T^i + Y - E^i$$

where again SW^i is defined as in equation (4). Solving the social planner's problem yields the optimal output of $q_j^{i,NC} = \frac{n^i(a^i - c^i) - z^i(1+d^i)}{(n^i)^2}$ with the associated emission fees of $\tau^{i,NC} = \frac{z^i(n^i+1)(1+d^i) - n^i(a^i - c^i)}{(n^i)^2}$.

To identify whether each country has incentives to deviate from cooperative outcome, the following proposition compares the social welfare of country i when it chooses to deviate (i.e., chooses independent, non-cooperative policy), while country l chooses cooperative policy, to that when both countries choose the cooperative policy.

Proposition B.1. *Given country l cooperates, country i's welfare from deviating is higher than from cooperating, $SW^{i,NC,C} > SW^{i,C,C}$, if and only if*

$$n^i < \frac{2d^i + d^l + 3}{2(d^i + 1)} \equiv \bar{n}^i$$

Intuitively, when few firms compete in country i ($n^i < \bar{n}^i$), it is optimal for the country to defect as $SW^{i,NC,C} > SW^{i,C,C}$. However, when there is a sufficiently large number of firms in the country ($n^i > \bar{n}^i$), the pressure on the CPR and ensuing environmental damage increases due to larger aggregate output produced by all these firms. Consequently, having more firms reduces the deviating country's welfare enough to yield $SW^{i,NC,C} \leq SW^{i,C,C}$, whereby cooperative policy entails more stringent regulation that helps to cut down aggregate production.

Appendix C: Proofs of Lemmas, Corollaries, and Propositions

Proof of Lemma 1

Taking first-order condition for firm j's profit maximization problem yields $q_j^i(Q_{-j}^i, \tau^i) = \frac{a^i - c^i - Q_{-j}^i - \tau^i}{2}$. Imposing the symmetry condition, $q_j^i = q_k^i = q$, produces equilibrium output of $q_j^i(\tau^i) = \frac{a^i - c^i - \tau^i}{n^i + 1}$. Finally, substituting the output function into the profit function yields $\pi_j^i(\tau^i) = \left(\frac{a^i - c^i - \tau^i}{n^i + 1}\right)^2$. ■

Proof of Lemma 2

Firm j's equilibrium output under no regulation is recovered by setting $\tau^i = 0$ in the equilibrium output function in Lemma 1, which yields $q_j^{i,U} = \frac{a^i - c^i}{n^i + 1}$. Then, the aggregate equilibrium output is $Q^{i,U} = n^i q_j^{i,U}$. The equilibrium firm profits is $\pi_j^{i,U} = \left(\frac{a^i - c^i}{n^i + 1}\right)^2$ and the equilibrium consumer surplus is $CS^{i,U} = \frac{1}{2}\left(Q^{i,U}\right)^2$. The residual amount of the CPR is $Y^U = \bar{Y} - z^i Q^{i,U} - z^l Q^{l,U}$ with the total environmental damage of $E^{i,U} = d^i\left(z^i Q^{i,U} + z^l Q^{l,U}\right)$. Finally, country i's social welfare corresponding to unregulated market environment is $SW^{i,U} = n^i \pi_j^{i,U} + CS^{i,U} + Y^U - E^{i,U}$. ■

Proof of Proposition 1

In the first stage, the first-order condition for the social planner's problem yields $q_j^i(Q_{-j}^i) = \frac{n^i(a^i - c^i) - Q_{-j}^i(n^i - 1) - z^i(1 + d^i)}{2n^i - 1}$. By symmetry, $q_j^i = q_k^i = q$, and hence firm j's socially optimal output level is $q_j^{i,NC} = \frac{n^i(a^i - c^i) - z^i(1 + d^i)}{(n^i)^2}$, where $\frac{\partial q_j^{i,NC}}{\partial z^i} = -\frac{d^i}{(n^i)^2} < 0$ and $\frac{\partial q_j^{i,NC}}{\partial d^i} = -\frac{z^i}{(n^i)^2} < 0$.

The environmental tax is recovered by setting $q_j^i(\tau^i) = q_j^{i,NC}$ and solving for τ^i:

$$\tau^{i,NC} = \frac{z^i(n^i+1)(1+d^i) - n^i(a^i - c^i)}{(n^i)^2}$$

where $\frac{\partial \tau^{i,NC}}{\partial z^i} = \frac{(n^i+1)(1+d^i)}{(n^i)^2} > 0$ and $\frac{\partial \tau^{i,NC}}{\partial d^i} = \frac{z^i(n^i+1)}{(n^i)^2} > 0$.

Plugging $q_j^{i,NC}$ and $\tau^{i,NC}$ in firm j's profit function, and using the symmetry condition $q_j^i = q_k^i = q$, we obtain

$$\pi_j^{i,NC} = \frac{\left(n^i(a^i - c^i) - z^i(1+d^i)\right)^2}{(n^i)^4}$$

The efficient aggregate output level is $Q^{i,NC} = n^i q_j^{i,NC}$ and the consumer surplus is $CS^{i,NC} = \frac{1}{2}\left(Q^{i,NC}\right)^2$. The residual amount of the CPR is $Y^{NC} = \bar{Y} - z^i Q^{i,NC} - z^l Q^{l,NC}$ and the total impact of the CPR's depletion is given by $E^{i,NC} = d^i\left(z^i Q^{i,NC} + z^l Q^{l,NC}\right)$. Finally, the resulting social welfare is $SW^{i,NC} = n^i \pi_j^{i,NC} + CS^{i,NC} + Y^{NC} - E^{i,NC}$. ■

Proof of Corollary 1

The optimal environmental policy is a tax $\tau^{i,NC} > 0$, i.e., $\frac{z^i(n^i+1)(1+d^i) - n^i(a^i-c^i)}{(n^i)^2} > 0$, if and only if

$$z^i > \frac{n^i(a^i - c^i)}{(n^i+1)(1+d^i)} \equiv \bar{z}_1$$

Also, it can be shown that $\frac{\partial \bar{z}_1}{\partial d^i} = -\frac{n^i(a^i-c^i)}{(n^i+1)(1+d^i)^2} < 0$. ■

Proof of Proposition 2

In the first stage, the first-order condition for the social planner's problem produces $q_j^i(Q_{-j}^i) = \frac{n^i(a^i-c^i) - Q_{-j}^i(n^i-1) - z^i(2+d^i+d^l)}{2n^i-1}$. By symmetry, $q_j^i = q_k^i = q$, and therefore firm j's socially optimal output level is $q_j^{i,C} = \frac{n^i(a^i-c^i) - z^i(2+d^i+d^l)}{(n^i)^2}$, where $\frac{\partial q_j^{i,C}}{\partial z^i} = \frac{-(2+d^i+d^l)}{(n^i)^2} < 0$ and $\frac{\partial q_j^{i,C}}{\partial d^i} = \frac{\partial q_j^{i,C}}{\partial d^l} =$

$\frac{-z^i}{(n^i)^2} < 0$. The environmental tax is computed by setting $q_j^i(\tau^i) = q_j^{i,C}$ and solving for τ^i:

$$\tau^{i,C} = \frac{z^i(n^i+1)(2+d^i+d^l) - n^i(a^i-c^i)}{(n^i)^2}$$

where $\frac{\partial \tau^{i,C}}{\partial z^i} = \frac{(n^i+1)(2+d^i+d^l)}{(n^i)^2} > 0$ and $\frac{\partial \tau^{i,C}}{\partial d^i} = \frac{\partial \tau^{i,C}}{\partial d^l} = \frac{z^i(n^i+1)}{(n^i)^2} > 0$.

Plugging $q_j^{i,C}$ and $\tau^{i,C}$ in firm j's profit function, and using the symmetry condition $q_j^i = q_k^i = q$, we obtain

$$\pi_j^{i,C} = \frac{\left(n^i(a^i-c^i) - z^i(2+d^i+d^l)\right)^2}{(n^i)^4}$$

The efficient aggregate production is $Q^{i,C} = n^i q_j^{i,C}$ and the corresponding consumer surplus is $CS^{i,C} = \frac{1}{2}\left(Q^{i,C}\right)^2$. The residual amount of the CPR is $Y^C = \bar{Y} - z^i Q^{i,C} - z^l Q^{l,C}$ and the total impact of the CPR's shrinking is $E^{i,C} = d^i\left(z^i Q^{i,C} + z^l Q^{l,C}\right)$. The resulting social welfare is $SW^{i,C} = n^i \pi_j^{i,C} + CS^{i,C} + Y^C - E^{i,C}$. ■

Proof of Corollary 2

The optimal environmental policy is a tax $\tau^{i,C} > 0$, i.e., $\frac{z^i(n^i+1)(2+d^i+d^l)-n^i(a^i-c^i)}{(n^i)^2} > 0$ if and only if

$$z^i > \frac{n^i(a^i-c^i)}{(n^i+1)(2+d^i+d^l)} \equiv \bar{z}_2$$

It can be shown that $\frac{\partial \bar{z}_2}{\partial d^i} = \frac{\partial \bar{z}_2}{\partial d^l} = -\frac{n^i(a^i-c^i)}{(n^i+1)(2+d^i+d^l)^2} < 0$. Moreover, since $\bar{z}_2 = \bar{z}_1 \cdot \frac{1+d^i}{2+d^i+d^l}$, where $\frac{1+d^i}{2+d^i+d^l} < 1$, cutoff $\bar{z}_2$ lies strictly below cutoff $\bar{z}_1$ for all parameter values. ■

Proof of Lemma 3

This can easily be shown by taking the difference of two environmental policies. In particular, when $z^i > \bar{z}_2$, both the cooperative and non-cooperative policies entail a taxation, $\tau^{i,C} > 0$

and $\tau^{i,NC} > 0$. The difference yields

$$\begin{aligned}\tau^{i,C} - \tau^{i,NC} &= \frac{z^i(n^i+1)(2+d^i+d^l) - n^i(a^i-c^i)}{(n^i)^2} - \frac{z^i(n^i+1)(1+d^i) - n^i(a^i-c^i)}{(n^i)^2} \\ &= \frac{z^i(n^i+1)(1+d^l)}{(n^i)^2}\end{aligned}$$

where $\tau^{i,C} - \tau^{i,NC} > 0 \implies \tau^{i,C} > \tau^{i,NC}$ under all admissible parameter values. Furthermore, we can show that $\frac{\partial(\tau^{i,C}-\tau^{i,NC})}{\partial z^i} = \frac{(n^i+1)(1+d^l)}{(n^i)^2} > 0$, $\frac{\partial(\tau^{i,C}-\tau^{i,NC})}{\partial d^i} = 0$, and $\frac{\partial(\tau^{i,C}-\tau^{i,NC})}{\partial d^l} = \frac{z^i(n^i+1)}{(n^i)^2} > 0$, respectively.

When $z^i \in (\bar{z}_1, \bar{z}_2)$, firms face a taxation with the cooperative policy, whereas they receive a subsidy under non-cooperative policy, $\tau^{i,C} > 0$ and $\tau^{i,NC} < 0$. Hence, $\tau^{i,C} > \tau^{i,NC}$ in this scenario.

On the other hand, when $z^i \in (0, \bar{z}_1)$, both regulatory settings entail a subsidy, $\tau^{i,C} < 0$ and $\tau^{i,NC} < 0$. The difference of absolute values yields

$$\begin{aligned}|\tau^{i,C}| - |\tau^{i,NC}| &= -\frac{z^i(n^i+1)(2+d^i+d^l) - n^i(a^i-c^i)}{(n^i)^2} + \frac{z^i(n^i+1)(1+d^i) - n^i(a^i-c^i)}{(n^i)^2} \\ &= -\frac{z^i(n^i+1)(1+d^l)}{(n^i)^2}\end{aligned}$$

where $|\tau^{i,C}| - |\tau^{i,NC}| < 0 \implies |\tau^{i,C}| < |\tau^{i,NC}|$ under all admissible parameter values. This implies that the non-cooperative policy entails a larger subsidy than cooperative policy. We can then show that $\frac{\partial(\tau^{i,C}-\tau^{i,NC})}{\partial z^i} = \frac{(n^i+1)(1+d^l)}{(n^i)^2} > 0$, $\frac{\partial(\tau^{i,C}-\tau^{i,NC})}{\partial d^i} = 0$, and $\frac{\partial(\tau^{i,C}-\tau^{i,NC})}{\partial d^l} = \frac{z^i(n^i+1)}{(n^i)^2} > 0$, respectively. ■

Proof of Lemma 4

We can show that

$$q_j^{i,U} - q_j^{i,NC} = \frac{z^i(1+d^i)(1+n^i) - n^i(a^i-c^i)}{(n^i)^2(1+n^i)}$$

where $q_j^{i,U} - q_j^{i,NC} > 0 \iff q_j^{i,U} > q_j^{i,NC}$ if and only if $z^i > \frac{n^i(a^i-c^i)}{(1+n^i)(1+d^i)}$, which is a condition required for $\tau^{i,NC} > 0$, i.e., cutoff $\bar{z}_1$. Also, $\frac{\partial(q_j^{i,U}-q_j^{i,NC})}{\partial z^i} = \frac{1+d^i}{(n^i)^2} > 0$ and $\frac{\partial(q_j^{i,U}-q_j^{i,NC})}{\partial d^i} = \frac{z^i}{(n^i)^2} > 0$. Similarly, we can demonstrate that

$$q_j^{i,U} - q_j^{i,C} = \frac{z^i(2+d^i+d^l)(1+n^i) - n^i(a^i-c^i)}{(n^i)^2(1+n^i)}$$

where $q_j^{i,U} - q_j^{i,C} > 0 \iff q_j^{i,U} > q_j^{i,C}$ if and only if $z^i > \frac{n^i(a^i-c^i)}{(1+n^i)(2+d^i+d^l)}$, which is a condition needed for $\tau^{i,C} > 0$, i.e., cutoff $\bar{z}_2$. Also, $\frac{\partial(q_j^{i,U}-q_j^{i,C})}{\partial z^i} = \frac{2+d^i+d^l}{(n^i)^2} > 0$ and $\frac{\partial(q_j^{i,U}-q_j^{i,C})}{\partial d^i} = \frac{\partial(q_j^{i,U}-q_j^{i,C})}{\partial d^l} = \frac{z^i}{(n^i)^2} > 0$. Finally, it can be shown that

$$q_j^{i,NC} - q_j^{i,C} = \frac{z^i(1+d^l)}{(n^i)^2}$$

where $q_j^{i,NC} - q_j^{i,C} > 0 \iff q_j^{i,NC} > q_j^{i,C}$ under all admissible parameter values. Also, $\frac{\partial(q_j^{i,NC}-q_j^{i,C})}{\partial z^i} = \frac{1+d^l}{(n^i)^2} > 0$ and $\frac{\partial(q_j^{i,NC}-q_j^{i,C})}{\partial d^l} = \frac{z^i}{(n^i)^2} > 0$. ■

Proof of Proposition 3

Comparing equilibrium profits without regulation ($\pi_j^{i,U}$) against that with non-cooperative regulation ($\pi_j^{i,NC}$), we can show that $\pi_j^{i,U} - \pi_j^{i,NC} > 0$, i.e., $\left(\frac{a^i-c^i}{n^i+1}\right)^2 - \frac{\left(n^i(a^i-c^i)-z^i(1+d^i)\right)^2}{(n^i)^4} > 0$, holds if and only if the appropriation rate satisfies

$$\bar{z}_1 < z^i < \frac{n^i(a^i-c^i)(1+2n^i)}{(n^i+1)(1+d^i)} \equiv \bar{z}_3$$

We can show that $\frac{\partial \bar{z}_3}{\partial d^i} = -\frac{n^i(a^i-c^i)(1+2n^i)}{(n^i+1)(1+d^i)^2} < 0$. Moreover, since $\bar{z}_3 = \bar{z}_1 \cdot (1+2n^i)$, cutoff $\bar{z}_1$ lies strictly below cutoff $\bar{z}_3$ for all parameter values. ■

Proof of Proposition 4

By comparing equilibrium profits without regulation ($\pi_j^{i,U}$) against that with non-cooperative regulation ($\pi_j^{i,C}$), we can show that $\pi_j^{i,U} - \pi_j^{i,C} > 0$, i.e., $\left(\frac{a^i-c^i}{n^i+1}\right)^2 - \frac{\left(n^i(a^i-c^i)-z^i(2+d^i+d^l)\right)^2}{(n^i)^4} > 0$, holds if and only if the appropriation rate satisfies

$$\bar{z}_2 < z^i < \frac{n^i(a^i - c^i)(1 + 2n^i)}{(n^i + 1)(2 + d^i + d^l)} \equiv \bar{z}_4$$

We can show that $\frac{\partial \bar{z}_4}{\partial d^i} = \frac{\partial \bar{z}_4}{\partial d^l} = -\frac{n^i(a^i-c^i)(1+2n^i)}{(n^i+1)(2+d^i+d^l)^2} < 0$. Moreover, since $\bar{z}_4 = \bar{z}_2 \cdot (1 + 2n^i)$ and $\bar{z}_4 = \bar{z}_3 \cdot \frac{1+d^i}{2+d^i+d^l}$, where $\frac{1+d^i}{2+d^i+d^l} < 1$, cutoff $\bar{z}_4$ lies strictly above cutoff $\bar{z}_2$ and strictly below cutoff $\bar{z}_3$ for all parameter values. Finally, $\bar{z}_4 > \bar{z}_1$, i.e., $\frac{n^i(a^i-c^i)(1+2n^i)}{(n^i+1)(2+d^i+d^l)} > \frac{n^i(a^i-c^i)}{(n^i+1)(1+d^i)}$, if and only if $d^i > \frac{1+d^l}{2n^i} - 1 \equiv \bar{d}$. ■

Proof of Proposition 5

Evaluating the difference between equilibrium profits under non-cooperative regulation ($\pi_j^{i,NC}$) and those under cooperative regulation ($\pi_j^{i,C}$), we can show that $\pi_j^{i,NC} - \pi_j^{i,C} > 0$, i.e., $\frac{\left(n^i(a^i-c^i)-z^i(1+d^i)\right)^2}{(n^i)^4} - \frac{\left(n^i(a^i-c^i)-z^i(2+d^i+d^l)\right)^2}{(n^i)^4} > 0$, holds if and only if the appropriation rate satisfies

$$0 < z^i < \frac{2n^i(a^i - c^i)}{3 + 2d^i + d^l} \equiv \bar{z}_5$$

We can show that $\frac{\partial \bar{z}_5}{\partial d^i} = -\frac{4n^i(a^i-c^i)}{(3+2d^i+d^l)^2} < 0$ and $\frac{\partial \bar{z}_5}{\partial d^l} = -\frac{2n^i(a^i-c^i)}{(3+2d^i+d^l)^2} < 0$. Moreover, $\bar{z}_5 > \bar{z}_4$, i.e., $\frac{2n^i(a^i-c^i)}{3+2d^i+d^l} > \frac{n^i(a^i-c^i)(1+2n^i)}{(n^i+1)(2+d^i+d^l)}$, if and only if $d^i < \bar{d}$. In addition, $\bar{z}_5 < \bar{z}_1$, i.e., $\frac{2n^i(a^i-c^i)}{3+2d^i+d^l} < \frac{n^i(a^i-c^i)}{(n^i+1)(1+d^i)}$, if and only if $d^i < \bar{d}$. Hence, cutoff $\bar{z}_5$ is bounded between $\bar{z}_1$ and $\bar{z}_4$, i.e., $\min\{\bar{z}_1, \bar{z}_4\} < z_5 < \max\{\bar{z}_1, \bar{z}_4\}$. ■

Proof of Corollary 3

Because firms in country i do not use the CPR in their production process ($z^i = 0$), they do not generate any negative externalities. Thus, the optimization problem of the social planner in country i under non-cooperative setting reduces to

$$\max_{\{q_j^i\}_{j=1}^{n^i}} \quad SW^i = n^i\left(a^i - q_j^i - Q_{-j}^i - c^i\right) q_j^i + \frac{1}{2}\left(q_j^i + Q_{-j}^i\right)^2 + \underbrace{(\bar{Y} - z^l Q^l) - d^i(z^l Q^l)}_{\text{transboundary externality}}$$

while under cooperative setting it is

$$\max_{\{q_j^i\}_{j=1}^{n^i}, \{q_j^l\}_{j=1}^{n^l}} \quad SW = SW^i + SW^l$$

where SW^i and SW^l are defined as in the non-cooperative case. Solving the maximization problem under both regulatory settings yields the same socially optimal output level $q_j^{i,NC} = q_j^{i,C} = \frac{a^i - c^i}{n^i}$. Setting the optimal firm output level equal to the equilibrium output level, i.e., $\frac{a^i - c^i}{n^i} = \frac{a^i - c^i - \tau^i}{n^i + 1}$, and solving for τ^i yields $\tau^{i,NC} = \tau^{i,C} = -\frac{a^i - c^i}{n^i} < 0$. ■

Proof of Corollary 4

When $d^i = 0$, emission fees satisfy

$$\tau^{i,NC}(d^i = 0) = \frac{z^i(n^i+1) - n^i(a^i - c^i)}{(n^i)^2} < \frac{z^i(n^i+1)(1+d^i) - n^i(a^i - c^i)}{(n^i)^2} = \tau^{i,NC}$$
$$\tau^{i,C}(d^i = 0) = \frac{z^i(n^i+1)(2+d^l) - n^i(a^i - c^i)}{(n^i)^2} < \frac{z^i(n^i+1)(2+d^i+d^l) - n^i(a^i - c^i)}{(n^i)^2} = \tau^{i,C}$$

Furthermore, profits under non-cooperative and cooperative regulation satisfy

$$\pi_j^{i,NC}(d^i = 0) = \frac{\left(n^i(a^i - c^i) - z^i\right)^2}{(n^i)^4} > \frac{\left(n^i(a^i - c^i) - z^i(1+d^i)\right)^2}{(n^i)^4} = \pi_j^{i,NC}$$
$$\pi_j^{i,C}(d^i = 0) = \frac{\left(n^i(a^i - c^i) - z^i(2+d^l)\right)^2}{(n^i)^4} > \frac{\left(n^i(a^i - c^i) - z^i(2+d^i+d^l)\right)^2}{(n^i)^4} = \pi_j^{i,C}$$

Profits satisfy $\pi_j^{i,U} > \pi_j^{i,NC}$ if and only if

$$\bar{z}_1(d^i = 0) \equiv \frac{n^i(a^i - c^i)}{n^i + 1} < z^i < \frac{n^i(a^i - c^i)(1+2n^i)}{n^i + 1} \equiv \bar{z}_3(d^i = 0)$$

Similarly, $\pi_j^{i,U} > \pi_j^{i,C}$ if and only if

$$\bar{z}_2(d^i = 0) \equiv \frac{n^i(a^i - c^i)}{(n^i+1)(2+d^l)} < z^i < \frac{n^i(a^i-c^i)(1+2n^i)}{(n^i+1)(2+d^l)} \equiv \bar{z}_4(d^i = 0)$$

Lastly, $\pi_j^{i,NC} > \pi_j^{i,C}$ if and only if

$$0 < z^i < \frac{2n^i(a^i - c^i)}{3+d^l} \equiv \bar{z}_5(d^i = 0) \quad \blacksquare$$

Proof of Corollary 5

When $d^l = 0$, cooperative emission fees satisfy

$$\tau^{i,C}(d^l = 0) = \frac{z^i(n^i+1)(2+d^i) - n^i(a^i - c^i)}{(n^i)^2} < \frac{z^i(n^i+1)(2+d^i+d^l) - n^i(a^i-c^i)}{(n^i)^2} = \tau^{i,C}$$

Moreover, profits under cooperative regulation satisfy

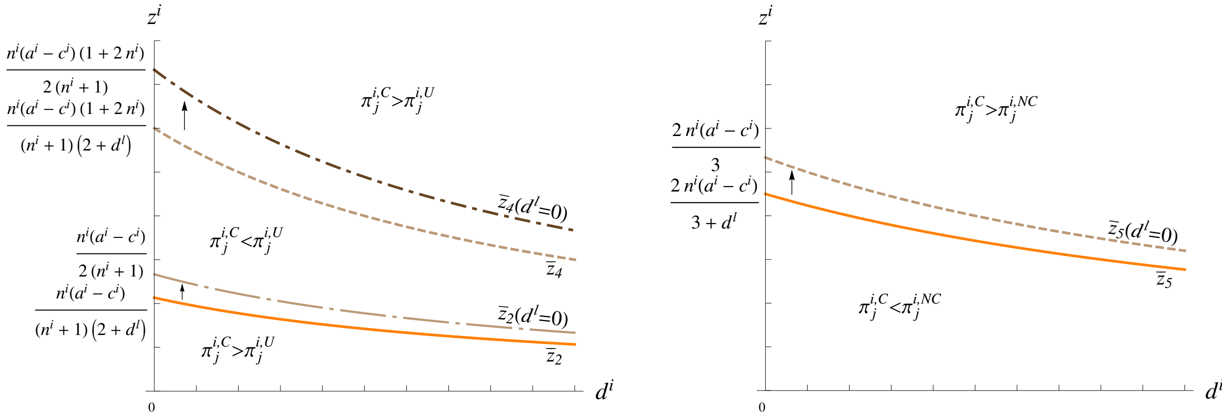
$$\pi_j^{i,C}(d^l = 0) = \frac{\left(n^i(a^i-c^i) - z^i(2+d^i)\right)^2}{(n^i)^4} > \frac{\left(n^i(a^i-c^i) - z^i(2+d^i+d^l)\right)^2}{(n^i)^4} = \pi_j^{i,C}$$

Profits satisfy $\pi_j^{i,U} > \pi_j^{i,C}$ if and only if

$$\bar{z}_2(d^l = 0) \equiv \frac{n^i(a^i - c^i)}{(n^i+1)(2+d^i)} < z^i < \frac{n^i(a^i-c^i)(1+2n^i)}{(n^i+1)(2+d^i)} \equiv \bar{z}_4(d^l = 0)$$

where $\bar{z}_2(d^l = 0) > \bar{z}_2$ and $\bar{z}_4(d^l = 0) > \bar{z}_4$.

In order to check if the area where profits satisfy $\pi_j^{i,U} > \pi_j^{i,C}$ contracts or expands when $d^l = 0$ (see Figure C.1(a)), we next evaluate the difference of regions for which $\pi_j^{i,U} > \pi_j^{i,C}$ and $\pi_j^{i,U}(d^l = 0) > \pi_j^{i,C}(d^l = 0)$.



(a) Cooperative (C) vs. no regulation (U) (b) Cooperative (C) vs. non-cooperative (NC)

Figure C.1: Firm preferences for different regulatory settings, $d^l = 0$

In particular,

$$
\begin{aligned}
R\left(\pi_j^{i,U} > \pi_j^{i,C}\right) &= \int_0^x \bar{z}_4 dd^i - \int_0^x \bar{z}_2 dd^i \\
&= \int_0^x \frac{n^i(a^i - c^i)(1 + 2n^i)}{(n^i + 1)(2 + d^i + d^l)} dd^i - \int_0^x \frac{n^i(a^i - c^i)}{(n^i + 1)(2 + d^i + d^l)} dd^i \\
&= \frac{(a^i - c^i)(n^i)^2 \log(\frac{2+x+d^l}{2+d^l})^2}{n^i + 1}
\end{aligned}
$$

and

$$
\begin{aligned}
R\left((\pi_j^{i,U}(d^l = 0) > \pi_j^{i,C}(d^l = 0)\right) &= \int_0^x \bar{z}_4(d^l = 0) dd^i - \int_0^x \bar{z}_2(d^l = 0) dd^i \\
&= \int_0^x \frac{n^i(a^i - c^i)(1 + 2n^i)}{(n^i + 1)(2 + d^i)} dd^i - \int_0^x \frac{n^i(a^i - c^i)}{(n^i + 1)(2 + d^i)} dd^i \\
&= \frac{(a^i - c^i)(n^i)^2 \log(\frac{2+x}{2})^2}{n^i + 1}
\end{aligned}
$$

Then, the difference of the above two quantities yields

$$
\begin{aligned}
R\left(\pi_j^{i,U} > \pi_j^{i,C}\right) - R\left(\pi_j^{i,U}(d^l=0) > \pi_j^{i,C}(d^l=0)\right) \quad &? \quad 0 \\
\frac{(a^i-c^i)(n^i)^2\log(\frac{2+x+d^l}{2+d^l})^2}{n^i+1} - \frac{(a^i-c^i)(n^i)^2\log(\frac{2+x}{2})^2}{n^i+1} \quad &? \quad 0 \\
\frac{2+x+d^l}{2+d^l} \quad &? \quad \frac{2+x}{2} \\
\text{(by assumption) } 0 \quad &< \quad d^l
\end{aligned}
$$

Hence, $R\left(\pi_j^{i,U} > \pi_j^{i,C}\right) < R\left(\pi_j^{i,U}(d^l=0) > \pi_j^{i,C}(d^l=0)\right)$, which implies that, when $d^l = 0$, the area in which firms favor no regulation relative cooperative regulation expands. This, in turn, implies that the complimentary area in which firms support cooperative regulation shrinks.

On the other hand, profits satisfy $\pi_j^{i,NC} > \pi_j^{i,C}$ if and only if

$$0 < z^i < \tfrac{2n^i(a^i-c^i)}{3+d^i} \equiv \bar{z}_5(d^l=0)$$

where $\bar{z}_5(d^l=0) > \bar{z}_5$. This indicates that the region in which $\pi_j^{i,NC} > \pi_j^{i,C}$ ($\pi_j^{i,NC} < \pi_j^{i,C}$) expands (shrinks, respectively) relative to when $d^l \neq 0$ (see Figure C.1(b)). ■

Proof of Corollary 6

The effect of market competition on preference regions (where firm prefers different regulatory settings) depicted in Figure 6 can be explored by taking the derivatives of the vertical intercepts of cutoffs z_1–z_5 with respect to n^i. In particular, we can show that:

- for z_1, $\frac{\partial}{\partial n^i}\frac{n^i(a^i-c^i)}{n^i+1} = \frac{a^i-c^i}{(n^i+1)^2} > 0$;
- for z_2, $\frac{\partial}{\partial n^i}\frac{n^i(a^i-c^i)}{(n^i+1)(2+d^l)} = \frac{a^i-c^i}{(2+d^l)(n^i+1)^2} > 0$;
- for z_3, $\frac{\partial}{\partial n^i}\frac{n^i(2n^i+1)(a^i-c^i)}{n^i+1} = \frac{(a^i-c^i)(1+2n^i(2+n^i))}{(n^i+1)^2} > 0$;
- for z_4, $\frac{\partial}{\partial n^i}\frac{n^i(2n^i+1)(a^i-c^i)}{(n^i+1)(2+d^l)} = \frac{(a^i-c^i)(1+2n^i(2+n^i))}{(2+d^l)(n^i+1)^2} > 0$;

- z_5, $\frac{\partial}{\partial n^i}\frac{2n^i(a^i-c^i)}{3+d^l} = \frac{2(a^i-c^i)}{3+d^l} > 0$;

which hold under all parameter values. This implies that when $n_i = 1$ (a decrease in the number of firms) cutoffs z_1–z_5 in Figure 6 shift downwards, thus expanding the region where firm profits are the greatest under cooperative regulation, while contracting the region where profits are the largest under non-cooperative regulation. By contrast, when $n_i \to \infty$ (an increase in the number of firms) cutoffs z_1–z_5 shift upwards, hence expanding the region where firm profits are the greatest under non-cooperative regulation, while shrinking the region where profits are the largest under cooperative regulation. ■

Proof of Lemma A.1

Sketch of proof: Follow the same steps as in the proof of Lemma 1, using the inverse demand function $p = a - Q$, where $Q = Q^i + Q^l = \sum_j^{n^i} q_j^i + \sum_k^{n^l} q_k^l$. ■

Proof of Lemma A.2

Sketch of proof: Follow the same steps as in the proof of Lemma 2. ■

Proof of Proposition A.1

Sketch of proof: Follow the same steps as in the proof of Proposition 1. ■

Proof of Proposition A.2

Sketch of proof: Follow the same steps as in the proof of Proposition 2. ■

Proof of Proposition A.3

Sketch of proof: Follow the same steps as in the proof of Proposition 3. ■

Proof of Proposition A.4

Sketch of proof: Follow the same steps as in the proof of Proposition 4. ■

Proof of Proposition B.1

Using equilibrium output levels for country i ($q_j^{i,NC}$) and country l ($q_j^{l,C}$), and emission fee for country i ($\tau^{i,NC}$) obtained in Appendix B, we can compute country i's social welfare from defecting (given country l cooperates) to be

$$\begin{aligned} SW^{i,NC,C} &= \frac{1}{2}\left((a^i-c^i)^2 - 2(d^i+1)(z^i(a^i-c^i)+z^l(a^l-c^l)) + 2\bar{Y}\right) \\ &+ \frac{(d^i+1)}{2}\left(\frac{2(z^l)^2(d^i+d^l+2)}{n^l} + \frac{(z^i)^2(d^i+1)(2n^i-1)}{(n^i)^2}\right) \end{aligned}$$

Similarly, using the outcomes from Proposition 2, we can compute country i's social welfare from cooperation (given country l cooperates) to be

$$\begin{aligned} SW^{i,C,C} &= \frac{1}{2}\left((a^i-c^i)^2 - 2(d^i+1)(z^i(a^i-c^i)+z^l(a^l-c^l)) + 2\bar{Y}\right) \\ &+ \frac{(d^i+d^l+2)}{2}\left(\frac{2(z^l)^2(d^i+1)}{n^l} + \frac{(z^i)^2(2n^i(d^i+1)-d^i-d^l-2)}{(n^i)^2}\right) \end{aligned}$$

We can show that

$$SW^{i,NC,C} - SW^{i,C,C} = \frac{(z^i)^2(d^l+1)\left(2d^i+d^l+3-2n^i(d^i+1)\right)}{2(n^i)^2}$$

which is positive if and only if

$$n^i < \frac{2d^i+d^l+3}{2(d^i+1)} \equiv \bar{n}^i \quad \blacksquare$$

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