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Multicountry Appropriation of the Commons, Externalities, and
Firm Preferences for Regulation

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Multicountry Appropriation of the Commons, Externalities, and Firm Preferences for Regulation*

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Abstract

This paper analyzes a common property resource (such as oil field or water reservoir) shared by two countries in the presence of two forms of bilateral externalities: the tragedy of the commons, and the environmental damage resulting from the exploitation of the resource. We demonstrate that both cooperative and non-cooperative forms of regulation produce a negative effect on firms' profits, as they increase firms' unit production costs. However, regulation can also entail a positive effect on profits, given that it mitigates industry overproduction. We show that the magnitude of these two effects depends not only on the type of regulatory instrument, but also on the rate of resource extraction and the environmental damage in each country. We identify conditions under which the positive effect of regulation dominates its negative effect, thus increasing firms' profits and ultimately incentivizing them to support the introduction of regulation, either at the national or international level.

KEYWORDS: Common property resource, Bilateral externalities, Transboundary externalities

JEL: H23, Q38, C71, C72

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1 Introduction

With economic growth and global population expansion, the pressure on the world's natural resources, such as fossil fuels, minerals, and freshwater, has increased dramatically over the last decades. Not only does unsustainable use of natural resources intensify the tragedy of the commons, it can also create different forms of environmental damage with local, regional, and international scope. Examples include rainforest exploitation, as it impacts air quality and intensifies global warming thus affecting the welfare of neighboring countries; and fisheries, since a large exploitation by firms in one country can disrupt the food chain, hindering the natural reproduction of other species fished and consumed in foreign countries.

In this paper, we investigate the management of common property resources (CPR) that are located between two countries in the presence of two forms of bilateral externalities: the tragedy of the commons and the environmental damage resulting from the exploitation of the commons. Gordon (1954) and Hardin (1968) highlighted early on that, in the absence of property rights, coercive laws or taxes, every rational agent has the incentive to exploit the commons at a level that is collectively inefficient. The presence of environmental externalities (e.g., environmental and transboundary pollution) associated with the exploitation of the commons complicates the regulators' task, as now the optimal policy has to balance the effects of multiple market failures, which generate different types of distortions, some at the domestic level and others with international scope. The situation becomes even more intricate if a natural resource occupies the geographical territories of two or more independent countries, hence allowing agents in both countries to use the resource. Since in this context the extraction of the resource by one agent reduces the resource available for domestic and foreign agents, even greater pressure will be placed on the stock of natural resources and the environment. While the literature has studied CPRs shared by multiple countries, it has largely overlooked the presence of environmental externalities that arise from the exploitation of the resource. However, externalities are relatively common in shared CPRs. For illustration purposes, we next provide four examples.

The South Pars/North Dome gas field. The South Pars/North Dome gas field is located in the Persian Gulf and is considered to be the largest offshore field in the world. The South Pars portion of the field lies in the territory of Iran, while the North Dome belongs to Qatar (see Figure A.1 in Appendix A). Because natural gas is actively extracted from the field by both countries, the pressure in the reservoir has been dropping over the years, thus increasing prospects for subsidence at the ground level. In particular, Taherynia et al. (2013) report many similarities between the South Pars/North Dome and collapsed Ekofisk oil field in Norway, and contend that there is a high potential for subsidence to occur in this field.¹

Alto Paraná Atlantic Forest. The Upper Paraná Atlantic Forest is one of the most biologically diverse and, at the same time, the most endangered rainforests on earth, covering the territories of southern Brazil, northeastern Argentina, and eastern Paraguay. Expansion of anthropogenic land uses in the rainforest, such as agriculture, cattle ranching, and extraction of timber for construction, furniture, and biofuel, led to severe forest fragmentation and degradation (see Figure A.2 in Appendix A), with only 7.4% of the original forest cover remaining (Di Bitetti et al., 2003). The deforestation at such extreme levels is a source of biodiversity loss, water cycle change, soil erosion, and global warming.

The Aral Sea. The depletion of the Aral Sea, and its dire economic, social, and environmental consequences that Central Asian countries have experienced for decades, is another stark example (see Figure A.3 in Appendix A). The Aral Sea, once considered to be the fourth-largest lake in the world, is located between Uzbekistan and Kazakhstan. The sea receives its waters from two rivers: Amu Darya, which flows across Afghanistan, Tajikistan, Turkmenistan and Uzbekistan, and Syr Darya, which flows across Kyrgyzstan, Uzbekistan,

¹Withdrawal of subsurface fluids and minerals can occasionally create voids in the earth, which expose large areas above the mine to ground subsidence (collapse) and seismic consequences. For instance, land subsidences of different magnitude were observed in the Groningen gas field in Slochteren, Netherlands (Ketelaar, 2009, p.15), the Ekofisk oil field in Norway (Sulak and Danielsen, 1989), the Wilmington oil field in California, United States (Mayuga and Allen, 1969), the Goose Creek oil field in Texas, United States (Coplin and Galloway, 1999) and the Retsof salt mine in New York, United States (Kappel et al., 1999). The impact of land subsidence and mine collapse includes reduction of quantity and quality of potable groundwater supplies, reduced air quality due to the release of natural gases to the atmosphere, and structural damage to homes, businesses, agricultural lands, public utilities, and cultural resources (Kappel et al., 1999).

Tajikistan and Kazakhstan. Heavy irrigation, a practice inherited from Soviet era, for water-intensive crops such as cotton and rice, and construction of hydroelectric dams severely reduced the amount of water flowing into the sea (see Figure A.4 in Appendix A), which ultimately caused the sea to shrink, thereby creating one of the worst ecological disasters in Central Asia. Specifically, the decline of the Aral Sea drastically changed regional climate, landscape, river flow, water level and salinity, fish population dynamics, soil fertility and public health.² Moreover, the rivalries and disagreements over the rights to water use have further exacerbated the situation, hindering cooperation in the sustainable management of water resources between basin countries (Peachey, 2004).

Lake Chad. The disappearance of Lake Chad, once the second-largest wetland in Africa, is another example of the tragedy of the shared commons where environmental externalities emerge (see Figure A.5 in Appendix A). Situated between Cameroon, Chad, Nigeria and Niger, the lake is fed by the Chari, Yobe, Ngadda and Yedseram rivers. Increased water demand from the local population, and inefficient damming and irrigation methods have led to significant reductions in the flows of the rivers that drain into the lake. As a result, the lake has shrunk dramatically within the last 40 years, affecting local economies, environment, and public health, and stirring conflicts among basin countries competing for increasingly scarce water (Odada et al., 2005).

In the present paper, we examine the appropriation and management of shared natural resources using a two-stage complete information game where, first, the regulators in two countries implement a Pigouvian policy (tax or subsidy), and second, firms, whose production is driven by resource-extraction, simultaneously and independently select profit-maximizing levels of appropriation given the policy set by the regulator. For completeness, we consider both non-cooperative regulation, where each country independently sets its own environmental policy, and cooperative regulation, where countries select the policy that maximizes their joint welfare as part of an international environmental agreement.

²For in-depth review, see Glantz (1999), O'Hara et al. (2000), Whish-Wilson (2002), and Philip and Aladin (2008).

We demonstrate that environmental regulation imposes two opposing effects on firms' profits. On one hand, more stringent regulation increases firms' production costs, thus imposing a *negative effect* on profits. On the other hand, tighter regulation helps firms mitigate aggregate production and thereby increase market prices, yielding a *positive effect* on profits. The magnitude of these two effects depends on the extraction rate and the extent of environmental damage, and are more pronounced with a cooperative policy as it entails stricter regulation relative to a non-cooperative policy.

Comparing the relative sizes of these effects, our findings suggest that when the appropriation rate is relatively high, both cooperative and non-cooperative policies entail stringent taxation, which imposes a negative effect on profits. However, such a strict taxation also helps to significantly mitigate industry overproduction, which in turn increases prices, ultimately producing a positive effect on profits that completely outweighs the negative effect imposed by the same regulation. Therefore, firms in this setting earn larger profits when environmental policy is present than when it is absent. Since cooperative policy is tighter than non-cooperative policy, the net effect of regulation is going to be larger under the former than the latter. As a consequence, firms support their countries' participation in international environmental agreements that coordinate environmental policies when such cooperation is needed (i.e., when bilateral externalities are high). This may provide an additional explanation for why some oil-rich middle Eastern countries that share oil fields may find it beneficial to be the members of the Organization of the Petroleum Exporting Countries (OPEC),³ an international organization that ensures stable energy markets, sustainable oil production, and environmental sustainability.⁴

In contrast, when the appropriation rate is moderate, regulation entails larger negative than positive effect on firm profits, as laxer policy instruments do not mitigate aggregate

³For instance, Iran and Iraq share the Al-Fakkah oil field; Iraq and Kuwait share the Rumaila oil field; and Kuwait and Saudi Arabia share the Khafji oil field; and all four countries are OPEC members.

⁴As part of its effort to support the environment and sustainable development, OPEC requires from its member countries full, effective and sustained implementation of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, which represent coordinated international environmental agreements. For further details, visit http://www.opec.org/opec_web/en/press_room/315.htm.

production substantially. Hence, profits are lower in the presence of any form of regulation, which incentivizes firms to oppose regulation. Finally, when the appropriation rate is relatively low, firms receive a subsidy under both cooperative and non-cooperative regulation, which produces a large positive effect on profits. As non-cooperative policy is less stringent than cooperative policy, firms receive more generous subsidies with the former than the latter. As a result, firms would actually favor non-cooperative policy (i.e., domestic regulation) in this setting.

From a policy perspective, the theoretical predictions of our analysis allow regulatory agencies to better anticipate the industry reaction to potentially new environmental policies, either domestic or international. In addition, our study highlights the role that non-environmental policies play in influencing industry preferences towards different regulatory settings. Specifically, the dissemination of new technologies that allow firms to appropriate the shared CPR at higher rates would facilitate the emergence of settings where firms support cooperative regulation in international environmental agreements. Intuitively, as the extraction rate increases, more output will be delivered to the market, which entails a downward pressure on the price and thus firms' profits. The Pigouvian tax in this context helps firms alleviate industry overproduction and thereby reverse the price decline. Such effect will be more pronounced with cooperative than non-cooperative policy as the former entails tighter regulation than the latter.

1.1 Related Literature

Previous studies on CPRs primarily focus on contexts where the natural resource is located within a country or a community and its extraction does not entail environmental externalities.⁵ Our paper is motivated by the work of Markusen (1975) who analyzes the dependence and interaction between two countries in the presence of a bilateral externality. In particu-

⁵See, for example, Ostrom (1992), Ostrom et al. (1994), Bromley (1992), Baland and Platteau (1996) and Berkes and Folke (1998). In particular, this line of literature contends that the lack of cooperation between agents is often associated with over-exploitation of natural resources, whereas cooperative management would lead to an efficient consumption of the resource.

lar, the paper develops a model that separately analyzes natural resource exploitation and international pollution problems, which in turn limits its application to cases where both types of market failures co-exist (as in the case of the Upper Paraná Atlantic Forest and the Aral Sea, for instance). Our paper fills this gap in the literature by examining the consumption and management of shared CPR, where environmental externalities arise from resource extraction.

More recently, Lambertini and Leitmann (2013) develop a single country model of an industry that appropriates a natural resource and generates negative environmental externalities. The authors demonstrate that profit motives can facilitate investments in green technologies, and competition may ultimately yield positive long-run welfare effects. When multiple firms in a single country exploit the CPR, the social planner considers the tradeoff between the opposite effects of output expansion on market price on one side, and the intensity of resource exploitation and environmental externality on the other. In contrast, when two or more countries share the same CPR, the planner in each country has to consider not only the tradeoff between the benefits and costs of domestic firms' production, but also the negative externalities imposed by foreign firms' production (i.e., transboundary pollution) and the competition for the use of the CPR.

The present paper also relates to the literature analyzing the effect of regulation on profits and firm preferences towards regulation. Farzin (2003) shows that stricter environmental standards can lead firms to improve product quality, which can ultimately increase firm profits. In particular, he contends that if consumers are sufficiently sensitive to product quality, then higher quality products should in theory allow firms to attract higher demand, thereby increasing profits more than the reduction in them caused by the compliance costs. In line with this study, Porter (1991) and Porter and van der Linder (1995a,b) point out that environmental regulation can also stir R&D and innovation incentives, ultimately increasing firm profits.⁶ Firm support for tighter regulation has also been viewed as a form of "market pre-

⁶See Heyes (2009) for a review of this literature.

dation,” whereby firms, despite being subject to costly regulation, may still lobby in favor of stringent regulation in order to increase their rivals’ costs (Salop and Scheffman, 1983, 1987), alleviate their cost-disadvantage (Muñoz-García and Akhundjanov, 2016), drive competitors out of the industry (Ordover and Willig, 1981), and deter potential entry into the market (Maloney and McCormick, 1982). We demonstrate that, even if quality, innovation, and “market predation” incentives are absent, firms can still support the introduction of environmental regulation as such regulation can allow firms to mitigate industry overproduction thereby producing a substantial positive effect on their profits.

The paper is organized as follows. In the following section, we present the model, and in Sections 3-4 we describe equilibrium firm output levels, profits, and emission standards under different regulatory contexts. Section 5 provides the analysis of output and profit comparisons, while Section 6 presents comparative statics of our results. Section 7 concludes.

2 Model

Consider two neighboring countries, indexed as $i = \{A, B\}$, with n^i identical firms in each. Firms produce a homogeneous product within a country, but the type of products can vary across the two countries (e.g., agricultural product and hydroelectric power). We assume that the two products, whose production requires natural resource extraction, are not traded between the two countries and, hence, firms in each country compete only against their domestic rivals.⁷ This assumption helps us focus on the effects of bilateral externalities on

⁷The two countries under consideration are, for instance, in political dispute or underdeveloped, and hence no significant amount of trade takes place between them. For example, Iran holds the world’s second largest gas reserves and shares a number of onshore and offshore fields with neighboring countries, including Qatar (e.g., the South Pars/North Dome), Iraq, Kuwait, and Saudi Arabia. Yet, Iran has been practically absent from the regional and global markets due to geopolitical tension and disputes over property rights, gas prices, and national interests. The country’s gas trade has been limited to Armenia, Azerbaijan, Turkey, and Turkmenistan (Wietfeld, 2011; Jalilvand, 2014). In the context of the Aral Sea basin countries, products that are produced by appropriation of river water (that feeds the sea) are primarily for self-sufficiency or for trade with non-basin countries. For instance, Tajikistan, where the major part of Central Asia’s water resources originates, produces hydroelectricity exclusively for domestic consumption, with hydropower contributing to about 98 per cent of total electricity production in 2009 (Liu et al., 2013). Similarly, Uzbekistan obtained 12 percent of its total electricity generation from hydropower in 2010, which it consumed domestically

the interdependence of resource consumption decisions in two countries. For completeness, we discuss the implications of relaxing this assumption in Appendix B, and show that our results are qualitatively unaffected.

We consider inverse linear demand function $p^i = a^i - Q^i$, where $Q^i = \sum_{j=1}^{n_i} q_j^i$, and cost function $C(q_j^i) = c^i q_j^i$, where $c^i \geq 0$ (Lambertini and Leitmann, 2013; Lambertini, 2013). For ease of presentation, the CPR will be referred to as a lake basin, although other interpretations are possible. In their production, firms use river water, which passes through the territories of both countries. The initial stock of the river water is \bar{X} , while the residual amount is

$$X = \bar{X} - z^A Q^A - z^B Q^B, \quad (1)$$

where $z^i \geq 0$ is the appropriation rate of the river water; and we allow for rates to be asymmetric, i.e., $z^A > z^B$ or $z^A < z^B$. The river feeds a lake (a CPR) located between the two countries, whose initial stock is \bar{Y} . Due to evaporation, the lake naturally shrinks by $\beta\bar{Y}$ each period, where $\beta \in (0, 1)$, but that loss can be replenished with the inflow from the river. Specifically, in the absence of exploitation of the river, the evaporated amount of lake water is completely offset by the inflow from the river, i.e., $\beta\bar{Y} = \bar{X}$. However, in the presence of exploitation of the river, the residual amount of lake water drops to

$$\begin{aligned} Y &= (1 - \beta)\bar{Y} + X \\ &= \bar{Y} - \beta\bar{Y} + \bar{X} - z^A Q^A - z^B Q^B \\ &= \bar{Y} - z^A Q^A - z^B Q^B, \end{aligned} \quad (2)$$

where the first equality is due to the river's residual amount being $X = \bar{X} - z^A Q^A - z^B Q^B$,

(Kochnakyan, 2013). In addition, Uzbekistan produces cotton using the river water and exports it mainly to China, Bangladesh, Korea and Russia (International Cotton Advisory Committee, 2011) – countries that are not located in the Aral Sea drainage basin. Likewise, in case of Lake Chad, basin countries use the water predominantly for domestic consumption.

while the last equality originates from the property that $\beta\bar{Y} = \bar{X}$. Hence, firms' production entails a reduction in the lake's initial stock \bar{Y} by the amount $z^A Q^A + z^B Q^B$.⁸

When the lake shrinks, the exposed salt and chemical contaminants deposited at the lake floor cause damage to the surrounding environment and population health. (For other possible impacts of the depletion of the lake, refer to the Aral Sea example in the introduction) Since the basin of the lake is located between the two countries, both are affected by its depletion, regardless of each country's appropriation rate. For simplicity, we consider that each country's damage function is additively separable in the two countries' use of the commons. Following Sherstyuk et al. (2016), Duval and Hamilton (2002), Espínola-Arredondo and Zhao (2012), Espínola-Arredondo and Muñoz-García (2012), and Lambertini (2013), the total damage – that is, in addition to loss of a natural resource – borne to country i is captured by a linear function

$$E^i = d^i (z^i Q^i + z^l Q^l), \quad (3)$$

where $d^i \geq 0$ represents country i 's marginal damage from the CPR exploitation.

In our model, environmental damage results from the depletion of the natural resource (the reduction in \bar{Y} in Equation 2), and not necessarily from aggregate production ($Q^A + Q^B$). In particular, if the appropriation rate is insignificant because the resource has a rapid regeneration rate ($z^A, z^B \rightarrow 0$), then the pressure on the CPR will be negligible, and hence no environmental damage will ensue ($E^A, E^B \rightarrow 0$). Furthermore, our model embodies two standard settings as special cases: first, if the initial stock of the commons is sufficiently large

⁸Similar to the extraction of oil and gas, we could have directly stated that firms' production reduces the stock of the lake by $z^A Q^A + z^B Q^B$, instead of explaining the whole mechanism, i.e., how the amount of the river water falls by $z^A Q^A + z^B Q^B$ due to firms' production, which in turn translates into that much less water being delivered to the lake, thereby causing it to shrink. However, such approach would not mimic the reality: both farmers and hydroelectric power plants use the river water in their production processes, and not the salty and immobile lake water. More importantly, our delineation of the firm-river-lake mechanism opens new venues for future studies to explore, for instance, how the incorporation of other exogenous and endogenous shocks on the river system affect the findings of the current study. Specifically, one might wonder how a higher rate of evaporation of the river water (resulting from the absence of concrete river canals) changes the tradeoff between using the river water for industrial and agricultural purposes versus letting it flow and reach the lake.

$\bar{Y} \rightarrow \infty$, our model analyzes a standard international externality of production without CPR problems; second, if environmental damages are zero $d^i = 0$, the model instead examines a CPR in which firms' activities do not entail environmental pollution.

We analyze a static model of the commons with a two-stage complete information game (Sethi and Somanathan, 1996; McCarthy, 2001; Lambertini, 2013), where the time structure is as follows:⁹

1. The social planners in each country either cooperatively or non-cooperatively set the level of per-unit taxation or subsidy (τ^i) for the optimal appropriation of the CPR;
2. Given the policy set by the regulator, firms in each country simultaneously and independently choose their production levels to maximize profits.

Operating by backward induction, we first investigate firms' production decisions and profits in the second stage of the game.

3 Industry Equilibrium

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

$$\max_{q_j^i \geq 0} \pi_j^i = (a^i - q_j^i - Q_{-j}^i) q_j^i - (c^i + \tau^i) q_j^i, \quad (4)$$

where $Q_{-j}^i = \sum_{k \neq j} q_k^i$. In Lemma 1, we present firm's best response function and the corresponding equilibrium output. All proofs are relegated to the appendix (see Appendix C).

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

⁹Players in the CPR game may collect precise information on payoff functions with repeated interaction, communication, signaling, or inspection. Therefore, the agents may know the mapping between decisions and payoffs. See, for example, Hackett et al. (1994), Ostrom et al. (1994), Gardner et al. (1997), Herr et al. (1997), Keser and Gardner (1999), Walker et al. (2000), and Casari and Plott (2003).

We can readily see that equilibrium output is decreasing in Pigouvian policy τ^i and in the number of competing firms in the industry.

4 The Planning Problem

In what follows, we analyze the social planner's problem in the first stage of the game under three different regulatory settings.

4.1 No Regulation

In the absence of government intervention, $\tau^i = 0$, firms do not internalize the negative externalities of their production. Lemma 2 describes firms' production decisions in the unregulated market environment.

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

The equilibrium aggregate output $Q^{i,U}$, where U denotes “unregulated,” increases in the number of firms n^i in the market, whilst the individual firm's equilibrium output $q^{i,U}$ decreases in n^i . We next discuss our results when the government designs an appropriate Pigouvian policy (taxation or subsidy) to induce efficient production.

4.2 Non-Cooperative Regulation

In this section, we consider the case where the social planners in each country act non-cooperatively, and hence maximize domestic welfare while ignoring the externalities imposed by domestic firms on the neighboring country. Such a non-cooperative regulation, therefore, does not achieve a first-best outcome (which we explore in the next section), but a second-best.

Each country individually maximizes its social welfare function defined as

$$\max_{\{q_j^i\}_{j=1}^{n^i}} SW^i = PS^i + CS^i + T^i + Y - E^i, \quad i = \{A, B\}, \quad (5)$$

where $PS^i = n^i \pi_j^i$ is the producer surplus, $CS^i = \frac{1}{2} (q_j^i + Q_{-j}^i)^2$ is the consumer surplus, $T^i = Q^i \tau^i$ is the total tax revenue, $Y = \bar{Y} - z^i (q_j^i + Q_{-j}^i) - z^l Q^l$ is the residual amount of the CPR, and $E^i = d^i (z^i (q_j^i + Q_{-j}^i) + z^l Q^l)$ is the aggregate environmental damage ensuing the exploitation of the CPR. Notice that the appropriation rate z^i of the commons affects the social welfare through two connected channels: (i) z^i determines how fast the natural resource is exhausted, thus affecting the residual stock of the CPR, $Y = \bar{Y} - z^i Q^i - z^l Q^l$; and (ii) z^i determines the extent of environmental damage resulting from the exploitation of the CPR, $E^i = d^i (z^i Q^i + z^l Q^l)$.

In the following proposition, we specify the regulator's choice of Pigouvian policy, and the individual firm's equilibrium production.

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

$$\tau^{i,NC} = \frac{z^i (n^i + 1) (1 + d^i) - n^i (a^i - c^i)}{(n^i)^2}, \quad (6)$$

which yields an equilibrium output of $q_j^{i,NC} = \frac{n^i (a^i - c^i) - z^i (1 + d^i)}{(n^i)^2}$ for every firm j .

As with Pigouvian taxes, the non-cooperative policy ensures that the marginal benefit of domestic firms' production is equal to the marginal social cost borne domestically. In addition, $\tau^{i,NC}$ increases in both the appropriation rate z^i and damage parameter d^i . Intuitively, when firms' production becomes more intensive in the use of the natural resource or inflicts larger social costs (resulting from the associated environmental damage), the social planner imposes a more stringent Pigouvian policy so firms reduce their production to a sustainable level. As a consequence, the individual firm's equilibrium output $q_j^{i,NC}$ decreases in z^i and d^i . Let us next analyze under which conditions the social planner sets a tax or a subsidy

policy.

Corollary 1. *The non-cooperative policy is a tax, $\tau^{i,NC} > 0$, if and only if the appropriation rate satisfies $z^i > \frac{n^i(a^i - c^i)}{(n^i + 1)(1 + d^i)} \equiv \bar{z}_1$. Furthermore, $\frac{\partial \bar{z}_1}{\partial d^i} < 0$.*

Figure 1 depicts cutoff \bar{z}_1 as a function of d^i . When the appropriation rate z^i is relatively small, $z^i < \bar{z}_1$, firms' production imposes an insignificant pressure on the CPR, leading the planner to provide subsidies to domestic firms to bring up their production to an efficient level. In contrast, when the appropriation rate is relatively high, $z^i > \bar{z}_1$, firms' production exerts a significant effect on the residual amount of the CPR, leading the planner to choose a tax policy to curb a socially excessive production. Moreover, cutoff \bar{z}_1 decreases in d^i , implying that for a given appropriation rate z^i firms are subject to a more stringent Pigouvian policy as the environmental damage parameter d^i rises.

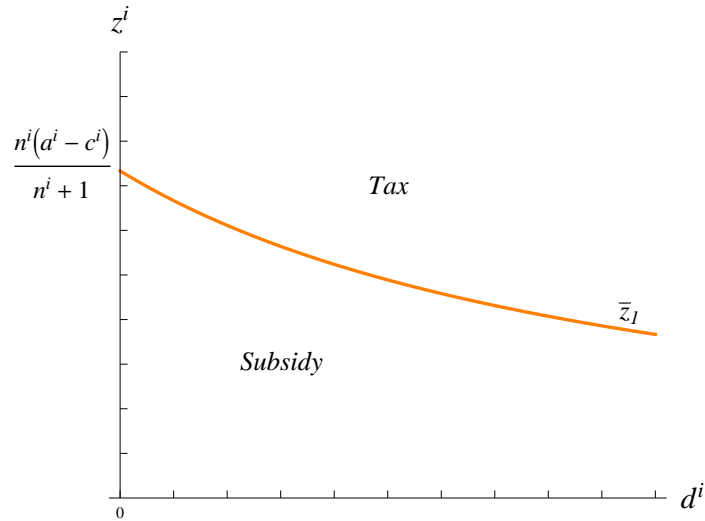


Figure 1: The optimal Pigouvian policy

4.3 Cooperative Regulation

In this section, we investigate the case where countries coordinate their policy design, e.g., by participating in international agreements. In the design of a Pigouvian policy, countries now fully internalize not only the internal effects of their home firms' production, but also

their external (transboundary) effects. As a consequence, environmental regulation achieves a first-best outcome.

In this context, countries maximize their joint social welfare by solving

$$\max_{\{q_j^i\}_{j=1}^{n^i}, \{q_j^l\}_{j=1}^{n^l}} SW = SW^i + SW^l, \quad (7)$$

where SW^i and SW^l , for $i, l = \{A, B\}$ and $i \neq l$, are defined as in the non-cooperative case. The following proposition identifies the Pigouvian policy that solves the above joint welfare maximization problem, and the output level that such policy induces each firm to produce.

Proposition 2. *Under cooperative (C) regulation, every country i sets*

$$\tau^{i,C} = \frac{z^i(n^i + 1)(2 + d^i + d^l) - n^i(a^i - c^i)}{(n^i)^2}, \quad (8)$$

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 .

Similar to the non-cooperative setting, the optimal Pigouvian policy $\tau^{i,C}$ increases in d^i , that is $\frac{\partial \tau^{i,C}}{\partial d^i} = \frac{\partial \tau^{i,NC}}{\partial d^i} = \frac{z^i(n^i + 1)}{(n^i)^2}$, whilst the optimal cooperative output $q_j^{i,C}$ decreases in d^i , that is $\frac{\partial q_j^{i,C}}{\partial d^i} = \frac{\partial q_j^{i,NC}}{\partial d^i} = -\frac{z^i}{(n^i)^2}$. However, unlike in the non-cooperative setting, cooperative Pigouvian policy (equilibrium output) is also increasing (decreasing, respectively) in the foreign damage parameter d^l , which reflects country i 's accountability for the transboundary effects of its domestic production. Intuitively, if the depletion of the CPR entails severe environmental damage in country l , then, under cooperative social planning, country i implements a tighter policy in order to disincentivize its domestic firms from producing large aggregate output, thereby mitigating the transboundary effects of their production. Moreover, notice that both Pigouvian policy and optimal output are more sensitive to domestic appropriation rate under cooperative than non-cooperative planning, i.e., $\frac{\partial \tau^{i,C}}{\partial z^i} = \frac{(n^i + 1)(2 + d^i + d^l)}{(n^i)^2} > \frac{(n^i + 1)(1 + d^i)}{(n^i)^2} = \frac{\partial \tau^{i,NC}}{\partial z^i}$ and $\frac{\partial q_j^{i,C}}{\partial z^i} = -\frac{(2 + d^i + d^l)}{(n^i)^2} < -\frac{(1 + d^i)}{(n^i)^2} = \frac{\partial q_j^{i,NC}}{\partial z^i}$. The reason for this is because the commons is shared between the two countries, and hence the

appropriation of the commons by domestic country reduces the resource availability not only for domestic, but also for foreign country. And vice versa. Consequently, cooperative policy accounts for the disutility caused to the foreign country from reduction in the quantity of the resource owing to the domestic country's consumption.

Similarly as in Corollary 1, we next identify conditions under which the Pigouvian policy in Proposition 2 is a tax or a subsidy.

Corollary 2. *The optimal policy is a tax, i.e., $\tau^{i,C} > 0$, if and only if the appropriation rate satisfies $z^i > \frac{n^i(a^i - c^i)}{(n^i + 1)(2 + d^i + d^l)} \equiv \bar{z}_2$, where $\bar{z}_2 < \bar{z}_1$ for all parameter values. Furthermore, $\frac{\partial \bar{z}_2}{\partial d^i} = \frac{\partial \bar{z}_2}{\partial d^l} < 0$.*

Similar to the non-cooperative scenario, when the appropriation rate of the commons is relatively low, $z^i < \bar{z}_2$, the social planner offers a subsidy to stimulate larger production from his domestic industry. In contrast, if domestic production is relatively intensive in the use of the CPR, $z^i > \bar{z}_2$, the planner introduces a tax policy in order to internalize the costs of firms' negative externalities. As depicted in Figure 2, cutoff \bar{z}_2 lies strictly below cutoff \bar{z}_1 for all $d^l > 0$, implying that the cooperative regulator chooses a tax policy under larger parameter conditions than the non-cooperative regulator. This is because the first-best policy $\tau^{i,C}$ internalizes the transboundary effects of resource extraction which are ignored by the second-best policy $\tau^{i,NC}$.

Both cutoffs are decreasing in d^i , reflecting that the set of appropriation rates for which firms receive subsidy (taxation) shrinks (expands, respectively) as the magnitude of the ensuing environmental damage increases. In addition, since only cutoff \bar{z}_2 is responsive to transboundary externalities, it shifts downwards (upwards) when the foreign damage parameter d^l increases (decreases, respectively). In the extreme case when $d^l \rightarrow 0$, the vertical intercept of cutoff \bar{z}_2 does not converge to that of cutoff \bar{z}_1 . The reason for the persistence of the distinction between the two regulatory regimes even with $d^l \rightarrow 0$ is because cooperative policy accounts for not only transboundary environmental damage but also the disutility caused to the neighboring country from a reduction in the size of the shared CPR.

Hence, so long as the countries appropriate the commons, $z^i > 0$, there will be at least one form of transboundary externality that the cooperative policy addresses (namely, the CPR exploitation).

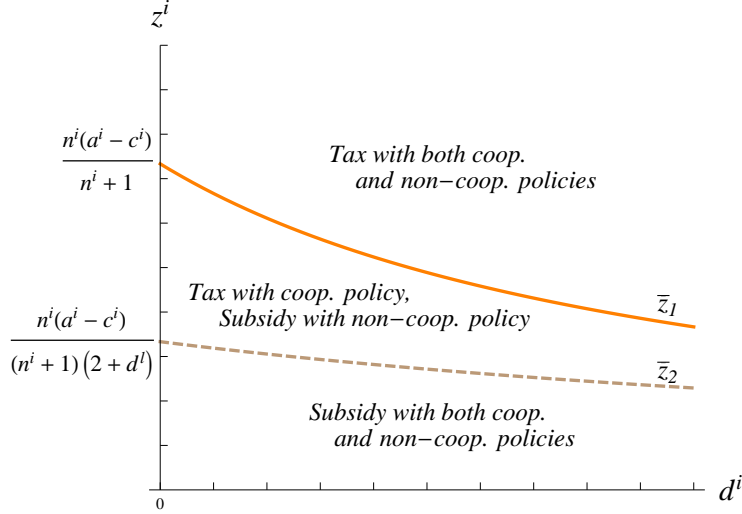


Figure 2: Cutoffs \bar{z}_1 and \bar{z}_2

5 Analysis

Let us next compare our results from unregulated and regulated (cooperative and non-cooperative) market environments. We first contrast Pigouvian policies arising under cooperative and non-cooperative regulations.

Lemma 3. *Cooperative regulation is more stringent than non-cooperative regulation, $\tau^{i,C} > \tau^{i,NC}$. Furthermore, the stringency premium $\tau^{i,C} - \tau^{i,NC}$ is increasing in both the appropriation rate z^i and the damage in country $l \neq i$, d^l , but unaffected by the damage in country i , d^i .*

The cooperative social planner choosing a stricter policy than the non-cooperative planner reflects the fact that the former curbs over-exploitation of the commons by inducing the output level that is jointly socially preferable. When z^i or d^i increases, *ceteris paribus*,

there will be a proportionate increase in both of these policy instruments. However, the wedge between non-cooperative and cooperative policy instruments increases in the domestic appropriation rate z^i and foreign damage parameter d^l as the values of these parameters determine the extent of transboundary externalities (i.e., depletion of the commons and the resulting environmental damage in a foreign country), which are only considered in the design of a cooperative policy but ignored in the non-cooperative case.

We next compare equilibrium output across different regulatory contexts.

Lemma 4. *Equilibrium output levels satisfy:*

- $q_j^{i,U} > q_j^{i,NC} > q_j^{i,C}$ if and only if $z^i > \bar{z}_1$, i.e., $\tau^{i,NC}, \tau^{i,C} > 0$;
- $q_j^{i,NC} > q_j^{i,U} > q_j^{i,C}$ if and only if $\bar{z}_2 < z^i < \bar{z}_1$, i.e., $\tau^{i,NC} < 0$ and $\tau^{i,C} > 0$;
- $q_j^{i,NC} > q_j^{i,C} > q_j^{i,U}$ if and only if $z^i < \bar{z}_2$, i.e., $\tau^{i,NC}, \tau^{i,C} < 0$.

When the appropriation rate is high, $z^i > \bar{z}_1$, the regulator imposes a tax policy under both cooperative and non-cooperative regulation, with the former being stricter than the latter as illustrated in Lemma 3. In this context, firms produce the highest amount of output when regulation is absent, followed by non-cooperative regulation, and finally cooperative regulation. When the appropriation rate is moderate, $\bar{z}_2 < z^i < \bar{z}_1$, non-cooperative regulation now opts for a subsidy policy, while cooperative regulation still chooses a tax. As a result, firms are able to produce the highest amount of output under non-cooperative setting (due to the incentives created by a subsidy), followed by unregulated setting, and finally the cooperative setting, where firms are still subject to a tax. Lastly, when the appropriation rate is relatively low, $z^i < \bar{z}_2$, the regulator provides a subsidy under both cooperative and non-cooperative settings. In this case, firms still produce the highest amount of output with non-cooperative regulation, as such regulation entails a more generous subsidy than under cooperative regulation, followed by cooperative regulation, and finally no regulation.

5.1 Profit Comparison

The introduction of regulation imposes two distinct effects on firms' profits: first, a *negative effect*, since a tax increases firms' marginal production costs ($c^i + \tau^i$); and second, a *positive effect*, since a tax leads firms to decrease their aggregate output (see Lemma 1), thus increasing prices and profits. Depending on the type of policy instrument (cooperative or non-cooperative), the magnitude of the two effects varies. In particular, the two effects are the most pronounced with cooperative policy as it entails more stringent regulation. In addition, we next show that the relative size of these effects, and thus firm preferences towards the regulatory setting, ultimately depends on the appropriation rate and the damage parameter. We compare firms' profits under each regulatory regime, and identify conditions under which the equilibrium profits can actually increase as a result of regulation.

5.1.1 No Regulation vs. Non-Cooperative Regulation

Proposition 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 $z^i < \bar{z}_1$ or $z^i > \bar{z}_3$, where*

$$\bar{z}_3 \equiv \frac{n^i(a^i - c^i)(1 + 2n^i)}{(n^i + 1)(1 + d^i)}. \quad (9)$$

Furthermore, $\bar{z}_3 > \bar{z}_1$ for all parameter values.

As illustrated in Figure 3, when the appropriation rate of the CPR is relatively low, $z^i < \bar{z}_1$, the pressure firms exert on the stock of natural resource and the environment is minimal, which results in the social planner providing subsidies to stimulate a larger production (see Corollary 1). Since the regulation in this context ameliorates firms' marginal production costs, firms, unsurprisingly, generate larger profits in the presence of regulation than in its absence, $\pi_j^{i,NC} > \pi_j^{i,U}$.

On the other hand, when the appropriation rate of the commons is moderate, $\bar{z}_1 < z^i < \bar{z}_3$, the industry production starts to inflict a considerable pressure on the CPR and the

environment, which in turn necessitates the imposition of a tax policy. Such policy, however, produces a negative effect on firm profits that outweighs its positive effect (i.e., mitigation of Cournot overproduction), ultimately decreasing firm profits, $\pi_j^{i,NC} < \pi_j^{i,U}$. In other words, the loss firms incur due to compliance costs is greater than the gain firms reap due to a decrease in aggregate production. As a consequence, the regulator faces the opposition of the resource-consuming industries when (z^i, d^i) pairs occur in this region.

Finally, when the appropriation rate of the CPR is relatively high, $z^i > \bar{z}_3$, firms earn larger profits when the regulation is present than when it is absent, $\pi_j^{i,NC} > \pi_j^{i,U}$. Intuitively, the social planner penalizes the resource-intensive industries with a more stringent taxation, which yields a large negative effect on firms' profits. However, such a strict policy substantially lowers aggregate output, which drives prices up, ultimately producing a large positive effect on profits that counterbalances the negative effect of the policy.

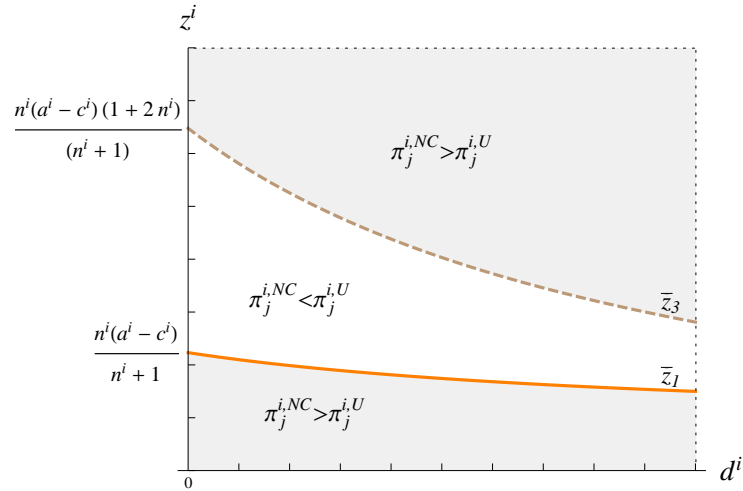


Figure 3: No regulation (U) vs. non-cooperative (NC) regulation

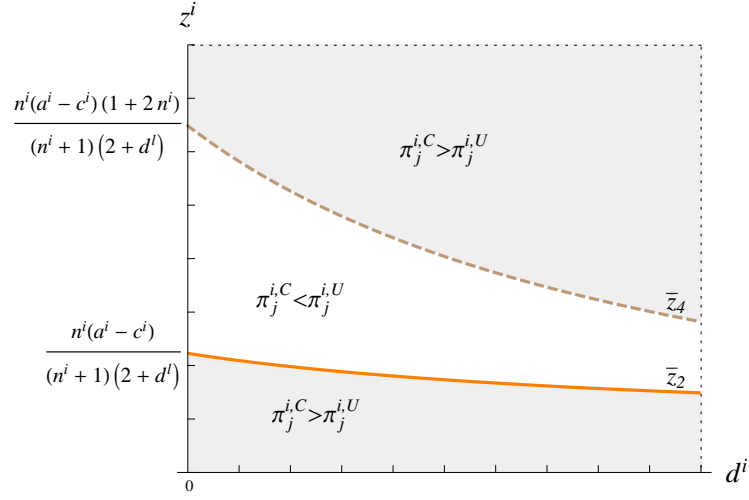


Figure 4: No regulation (U) vs. cooperative (C) regulation

5.1.2 No Regulation vs. Cooperative Regulation

Proposition 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 $z^i < \bar{z}_2$ or $z^i > \bar{z}_4$, where*

$$\bar{z}_4 \equiv \frac{n^i(a^i - c^i)(1 + 2n^i)}{(n^i + 1)(2 + d^i + d^l)}. \quad (10)$$

Furthermore, $\bar{z}_2 < \bar{z}_4 < \bar{z}_3$ for all parameter values, and $\bar{z}_4 > \bar{z}_1$ ($\bar{z}_4 < \bar{z}_1$) for all $d^i > \frac{1+d^l}{2n^i} - 1 \equiv \bar{d}$ ($d^i < \bar{d}$, respectively).

Firm preferences towards cooperative regulation thus exhibit a similar pattern as those towards non-cooperative policy (see Figure 4), except for the relative position of cutoffs that determine the set of (d^i, z^i) pairs for which firms either support or oppose regulation.

In particular, firms lobby in favor of the introduction of cooperative regulation when the appropriation rate is low, $z^i < \bar{z}_2$, where firms' enjoy a large positive effect of the subsidy; and when it is relatively high, $z^i > \bar{z}_4$, where the gains from the alleviation of industry overproduction offset the compliance costs of regulation. In contrast, firms oppose regulation when the appropriation rate is relatively moderate, $\bar{z}_2 < z^i < \bar{z}_4$, where now the compliance costs outweigh the profit gain. Since regulation is more stringent under cooperative than

non-cooperative policy, the magnitude of the negative and positive effects of regulation is higher under cooperative than non-cooperative policy. This is evident from the observation that the above two cutoffs lie strictly below their counterparts in the non-cooperative setting, i.e., $\bar{z}_2 < \bar{z}_1$ and $\bar{z}_4 < \bar{z}_3$.

5.1.3 Cooperative vs. Non-Cooperative Regulation

Proposition 5. *Firm's equilibrium profits under cooperative regulation are larger than under non-cooperative regulation, $\pi_j^{i,C} > \pi_j^{i,NC}$, if and only if $z^i > \bar{z}_5$, where*

$$\bar{z}_5 \equiv \frac{2n^i(a^i - c^i)}{3 + 2d^i + d^l}. \quad (11)$$

Furthermore, $\bar{z}_1 < \bar{z}_5 < \bar{z}_4$ ($\bar{z}_4 < \bar{z}_5 < \bar{z}_1$) for all $d^i > \bar{d}$ ($d^i < \bar{d}$, respectively).

Figure 5 depicts cutoff \bar{z}_5 along with \bar{z}_1 and \bar{z}_2 , cutoffs for Pigouvian subsidy/taxation under non-cooperative and cooperative regulation, respectively. The introduction of non-cooperative regulation is beneficial for firm profits relative to cooperative regulation if the appropriation rate is relatively low, $z^i < \bar{z}_5$. In particular, in region I, where $z^i < \bar{z}_2$, both forms of regulation entail a subsidy. Since non-cooperative policy entails a more generous subsidy than cooperative policy (see Lemma 3), the industry unambiguously favors the former policy in this region.

In region II, where $\bar{z}_2 < z^i < \min\{\bar{z}_1, \bar{z}_5\}$, firms receive a subsidy with non-cooperative regulation, whilst they face taxation under cooperative regulation. Since the appropriation rate in this context is relatively moderate, the cooperative regulation does not yield large enough positive effect (i.e., reduction in aggregate output), so as to outweigh the net effect that non-cooperative subsidy imposes on firm profits. Consequently, firms prefer non-cooperation regulation in this region. Finally, in region III, where $\bar{z}_1 < z^i < \bar{z}_5$, both cooperative and non-cooperative regulation entail taxation. Although the magnitude of positive effect is low under both regulatory settings (due to moderate appropriation rate

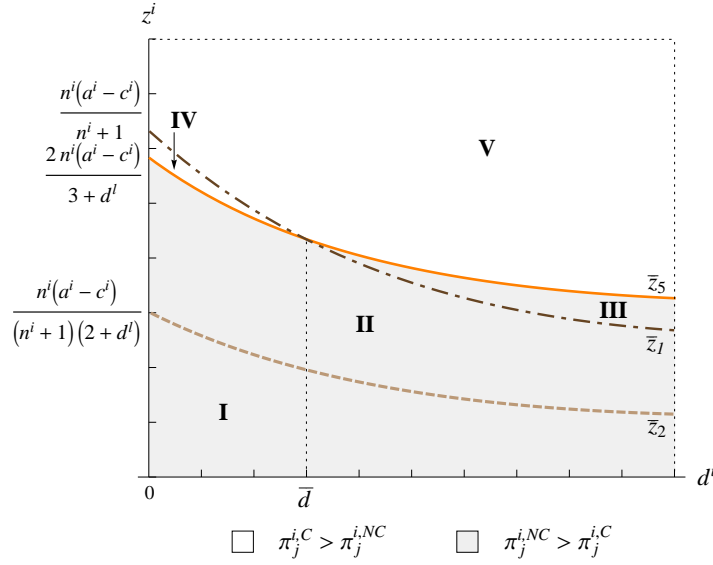


Figure 5: Cooperative (C) vs. non-cooperative (NC) regulation

which results in a laxer taxation), the magnitude of negative effect is nonetheless larger under cooperative than non-cooperative policy. Hence, firms prefer to lobby in favor of the non-cooperative regulation in this region.

In contrast, when $z^i > \bar{z}_5$, cooperative regulation becomes beneficial for firm profits relative to non-cooperative regulation. In region IV, where $\bar{z}_5 < z^i < \bar{z}_1$, even though non-cooperative policy entails a subsidy and cooperative policy assigns a tax, firms prefer the latter form of regulation. Such behavior can be rationalized as follows. Since the appropriation rate is relatively high in this context, the non-cooperative policy does not entail large subsidy (recall that $\tau^{i,NC}$ is decreasing in z^i). Hence, the positive effect of non-cooperative policy on firm profits will be relatively small. On the other hand, a high appropriation rate translates into stricter taxation under cooperative policy. Such policy imposes a large negative effect on firm profits, which forces the industry to significantly lower aggregate production, thus yielding a large positive effect on profits. As a consequence, the net effect of cooperative policy on profits is larger than that of non-cooperative policy.

In region V, where $z^i > \max\{\bar{z}_1, \bar{z}_5\}$, firms are subject to taxation under both regulatory

settings. The high extraction rate in this context forces the regulator to impose a stringent environmental policy which substantially depresses the output. As a result, the introduction of a Pigouvian policy helps firms alleviate industry overproduction, and hence produce an upward effect on the price. Such effect will be more pronounced with cooperative than non-cooperative policy as the former entails tighter regulation than the latter. Hence, in this region, firms benefit more from cooperative than non-cooperative regulation.

We summarize firms' preferences towards different regulatory settings in Figure 6, which superimposes cutoffs identified in the paper on the (d^i, z^i) -axis.¹⁰ It is clear that firms are better off with at least one form of regulation (cooperative or non-cooperative) relative to no regulation under a large set of parameter values. The regulation harms firms' profits only when the extraction rate is moderate, $\bar{z}_1 < z^i < \bar{z}_4$, and the environmental damage is sufficiently large, $d^i > \bar{d}$ (i.e., the shaded region). Intuitively, when the rate of the resource consumption is moderate, the social planner imposes a relatively lax tax on the industry. Such a policy, however, does not yield a sizable reduction in aggregate production (a positive effect), ultimately hurting firms' profits.

Furthermore, firms are better off with cooperative (non-cooperative) regulation when the appropriation rate of the CPR is relatively high (low, respectively). This result has important policy implications. In particular, it shows that when firms exhaust the shared natural resources at a higher rate, and create environmental damages that affect both domestic and foreign countries, then they are actually willing to support their countries' participation in international environmental agreements. In contrast, when firms exhaust the CPR at a relatively lower rate, they are in favor of non-cooperative policy. In other words, firms choose to support cooperative regulation when social costs of resource extraction are high (i.e., fast resource exhaustion and large-scale environmental damage), but go with domestic policies when these costs are relatively low.

¹⁰The relative position of the cutoffs and their intersection points are discussed in the proofs of Corollary 2 and Propositions 3, 4 and 5. For profit ranking and firm preferences towards regulation in different regions of the (d^i, z^i) quadrant, see the discussions following the aforementioned propositions.

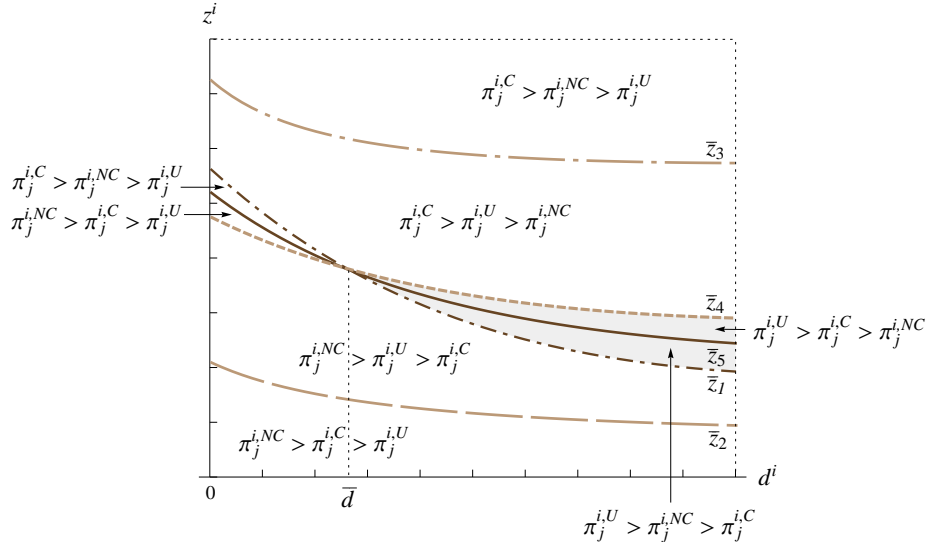


Figure 6: Firm preferences for different regulatory settings

6 Comparative Statistics

In this section, we examine the comparative statistics of our above profit comparisons. Specifically, we focus on how firm preferences for regulation are influenced by variations in appropriation rates and environmental damages. We first analyze our model in two special cases described in the introduction. First, a setting in which the appropriation rate is zero, because the CPR's natural regeneration rate is relatively fast, and thus regulators only face environmental damage. Second, a context in which the appropriation rate is positive but the environmental damage is zero, and thus the regulation only seeks to address the overexploitation of the CPR.

Corollary 3 (No CPR externality). *When the domestic appropriation rate is zero, $z^i = 0$, domestic firms generate zero environmental externalities, and the optimal cooperative and non-cooperative domestic policies set the same subsidy $\tau^{i,NC} = \tau^{i,C} = -\frac{a^i - c^i}{n^i} < 0$.*

Since environmental externalities emerge as a by-product of the appropriation of the commons, and not necessarily from firms' production activities, then when the extraction rate approaches zero, $z^i = 0$, so do the ensuing negative externalities of firm's production ac-

tivities. As a result, both cooperative and non-cooperative policies entail the same (subsidy) policy for the country that does *not* exploit the CPR. In particular, the optimal policy entails a subsidy so as to raise the underproduction in Cournot competition to a socially efficient level. Notice that the domestic country can still suffer from the transboundary externality, with a total disutility of $(\bar{Y} - z^l Q^l) - d^i(z^l Q^l)$, if firms located in a neighboring country continue to use the CPR in their production process, i.e., $z^l > 0$.¹¹

Let us now examine the second extreme case in which appropriation rates are positive but environmental damages are zero.

Corollary 4 (No environmental damage). *When the appropriation of the commons entails no domestic environmental damage, $d^i = 0$, domestic firms face less stringent cooperative and non-cooperative regulation, and earn larger profits than when $d^i > 0$. Furthermore, profits satisfy*

- $\pi_j^{i,NC} > \pi_j^{i,U}$ if and only if $z^i < \bar{z}_1(d^i = 0)$ or $z^i > \bar{z}_3(d^i = 0)$;
- $\pi_j^{i,C} > \pi_j^{i,U}$ if and only if $z^i < \bar{z}_2(d^i = 0)$ or $z^i > \bar{z}_4(d^i = 0)$;
- $\pi_j^{i,C} > \pi_j^{i,NC}$ if and only if $z^i > \bar{z}_5(d^i = 0)$.

In this case, the natural resource is exhausted without creating environmental pollution in the domestic country but it can still cause a transboundary externality if $d^l > 0$.¹² Because domestic firms' production creates fewer market failures in this context (i.e., no domestic environmental damages), the social planner imposes less stringent cooperative and non-cooperative regulation than when $d^i > 0$. Consequently, firms are able to earn larger profits with regulation compared to what they received when domestic damages were present.

The profit ranking of different regulatory settings remains the same as in Figure 6, with all cutoffs evaluated at $d^i = 0$, i.e., the vertical axis of Figure 6. In this context, firms' profits are

¹¹In a special case, when $z^i = z^l = 0$, no environmental externalities (i.e., neither tragedy of the commons nor environmental damage) will be generated.

¹²In a special case, when $d^i = d^l = 0$, the consumption of the CPR generates neither internal nor transboundary pollution in two countries, but can still lead to the tragedy of the commons.

unambiguously larger with some form of regulation (cooperative or non-cooperative) relative to no regulation at all. Indeed, as illustrated in the vertical axis of Figure 6, firms prefer cooperative regulation for all $z^i > \bar{z}_5$, but non-cooperative policy otherwise.

Let us next evaluate firm preferences for regulation when exploitation of the commons entails a domestic, but not a transboundary externality.

Corollary 5 (No transboundary damage). *When the appropriation of the commons entails no transboundary damage, $d^l = 0$, domestic firms face less stringent cooperative regulation and generate larger profits than when $d^l > 0$. Furthermore, profits satisfy*

- $\pi_j^{i,C} > \pi_j^{i,U}$ if and only if $z^i < \bar{z}_2(d^l = 0)$ or $z^i > \bar{z}_4(d^l = 0)$;
- $\pi_j^{i,C} > \pi_j^{i,NC}$ if and only if $z^i > \bar{z}_5(d^l = 0)$,

where the regions for which $\pi_j^{i,C} > \pi_j^{i,U}$ ($\pi_j^{i,C} < \pi_j^{i,U}$) and $\pi_j^{i,C} > \pi_j^{i,NC}$ ($\pi_j^{i,C} < \pi_j^{i,NC}$) shrinks (expands, respectively).

In this context, domestic extraction affects the neighboring country only through the disutility arising from the depletion of the shared CPR. As a result, the cooperative policy entails less stringent regulation, thus allowing firms to earn larger profits compared to that when $d^l > 0$. Since non-cooperative policy does not internalize the transboundary externalities, then changes in the foreign damage parameter does not affect domestic non-cooperative policy.

7 Discussion and Concluding Remarks

In the present study, we analyze the cooperative and non-cooperative management of a common property resource shared between two countries in the presence of two forms of bilateral externalities: the depletion of the commons and the environmental damage resulting from the consumption of the resource. We show that regulation can benefit not only the stock of the commons and environmental quality, but also firms' profits, thus inducing them

to actually support the introduction of regulation, either cooperative, through international environmental agreements, or non-cooperative, via independent national policies.

The paper demonstrates that the introduction of regulation imposes two opposing effects on profits: a negative effect, owing to an increase in marginal production costs, and a positive effect, due to the mitigation in Cournot overproduction. The magnitude of the two effects depends on the extraction rate and the environmental damage parameter, and are more pronounced with cooperative policy as it entails more stringent regulation relative to non-cooperative policy. Comparing the positive and negative effects of regulation, we show that firms are better off with at least one form of regulation under a large set of appropriation rates. In particular, firms reap the highest profits under cooperative regulation when the appropriation rate is relatively high, thus supporting their countries' participation in international environmental agreements when bilateral externalities are high. As the extraction rate decreases, regulation starts to impose smaller positive effect on profits (i.e., mitigation of aggregate production), thus incentivizing firms to oppose all forms of regulation. When the appropriation rate is sufficiently low, firms are better off with non-cooperative regulation as such regulation entails larger positive effect on profits (due to subsidies).

From a policy perspective, our theoretical predictions allow regulatory agencies to better anticipate the industry reaction to potentially new environmental policies. In particular, our study emphasizes the role that non-environmental policies play in influencing the industry preferences towards different regulatory settings. For instance, the dissemination of new technologies that allow firms to appropriate the CPR at higher rate would facilitate the emergence of settings where firms support cooperative regulation through international environmental agreements. Furthermore, measures taken to mitigate the extent of domestic environmental consequences of the appropriation of the CPR would give rise to settings where firms favor any form of regulation.

A number of research questions remain open. Our model considers a complete information setting, whereby information about each country's extraction rate and environmental

damages is common knowledge. A natural extension is to consider a setting where each country is privately informed about its appropriation and damages, but not those of foreign countries. Although governments might gather information about their neighbors' appropriation patterns, such information is not necessarily accurate. Furthermore, we use per unit fee/subsidy to regulate industry production. It would be interesting to examine firm preferences towards regulation under other types of policy instruments, such as tradable quotas and nonlinear taxes. Future studies can also extend our analysis by allowing for endogenous firm entry in both or one of the countries. In this context, apart from studying the effect of regulation on profits, it is of interest to examine whether regulation facilitates or hinders potential entry into the industry. Finally, future studies can explore the regulation of shared CPRs, and firm behavior, in the context of dynamic games.

Appendix A: Supplementary figures

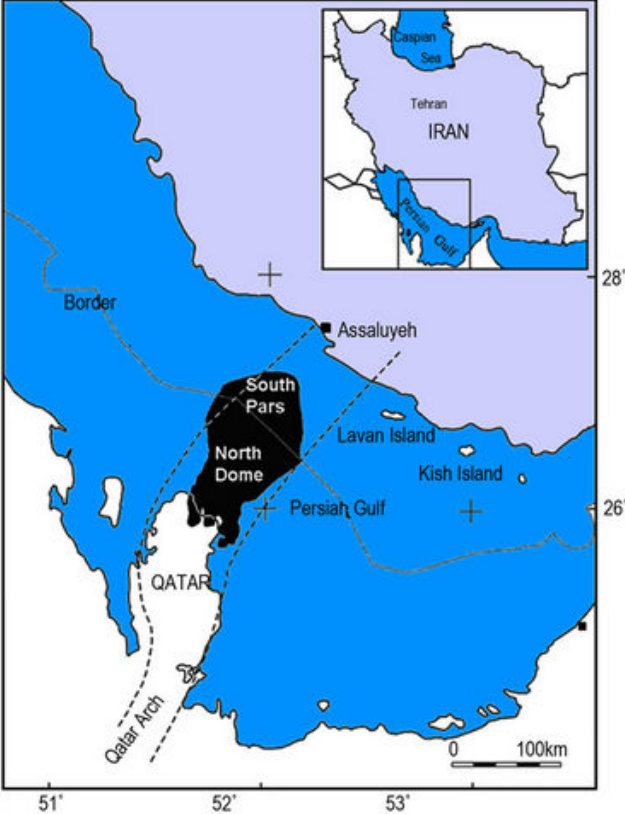


Figure A.1: The South Pars/North Dome gas field
(Source: Taherynia et al., 2013)

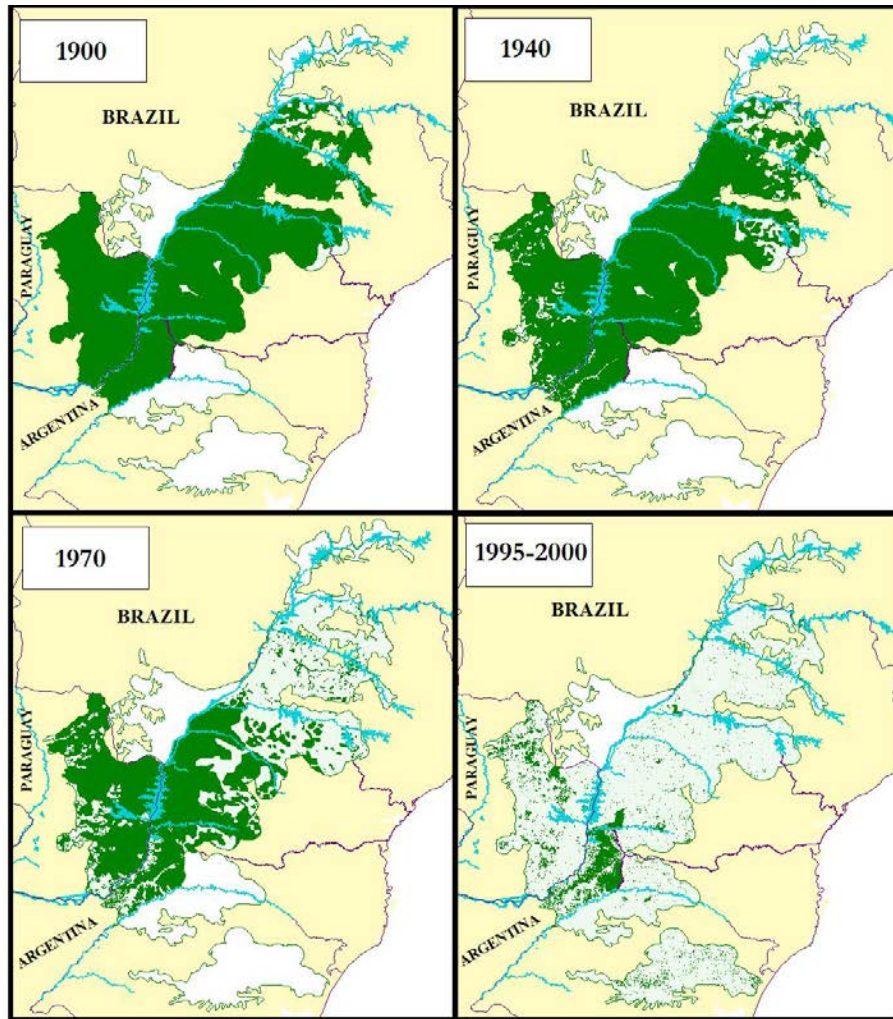


Figure A.2: The Upper Paraná Atlantic Forest
 (Source: Di Bitetti et al., 2003)

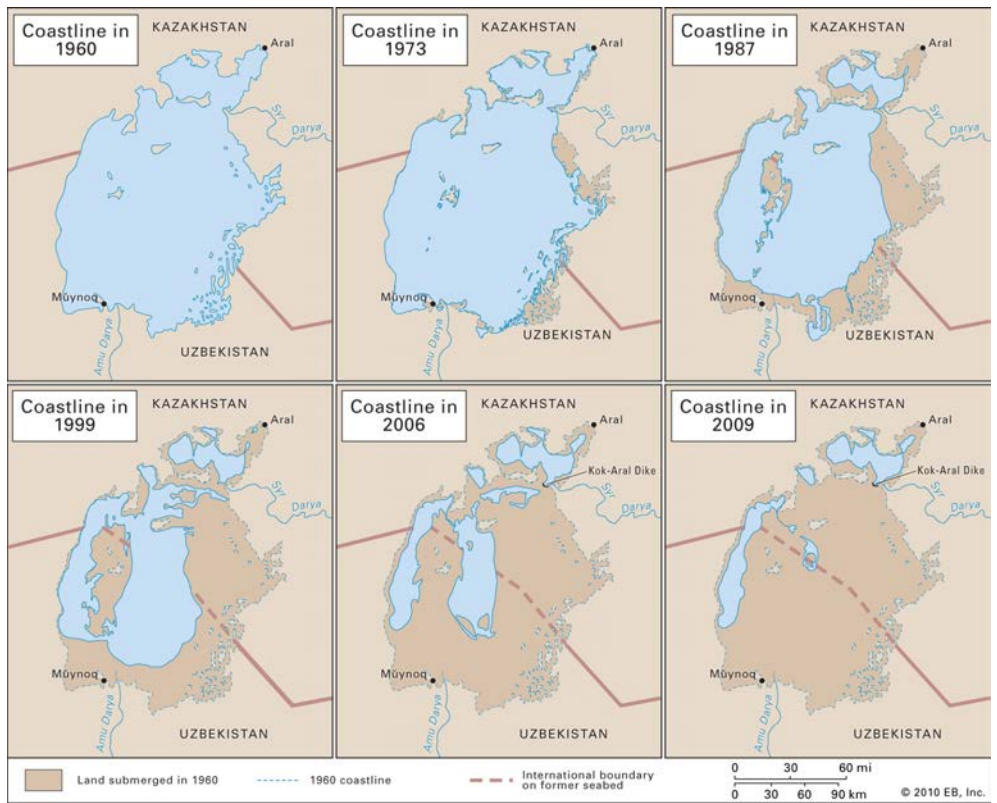


Figure A.3: Timeline of the Aral Sea basin's shrinking
 (Source: Encyclopaedia Britannica)



Figure A.4: Water resources of the Aral Sea basin
(Source: Zoë Environment Network)

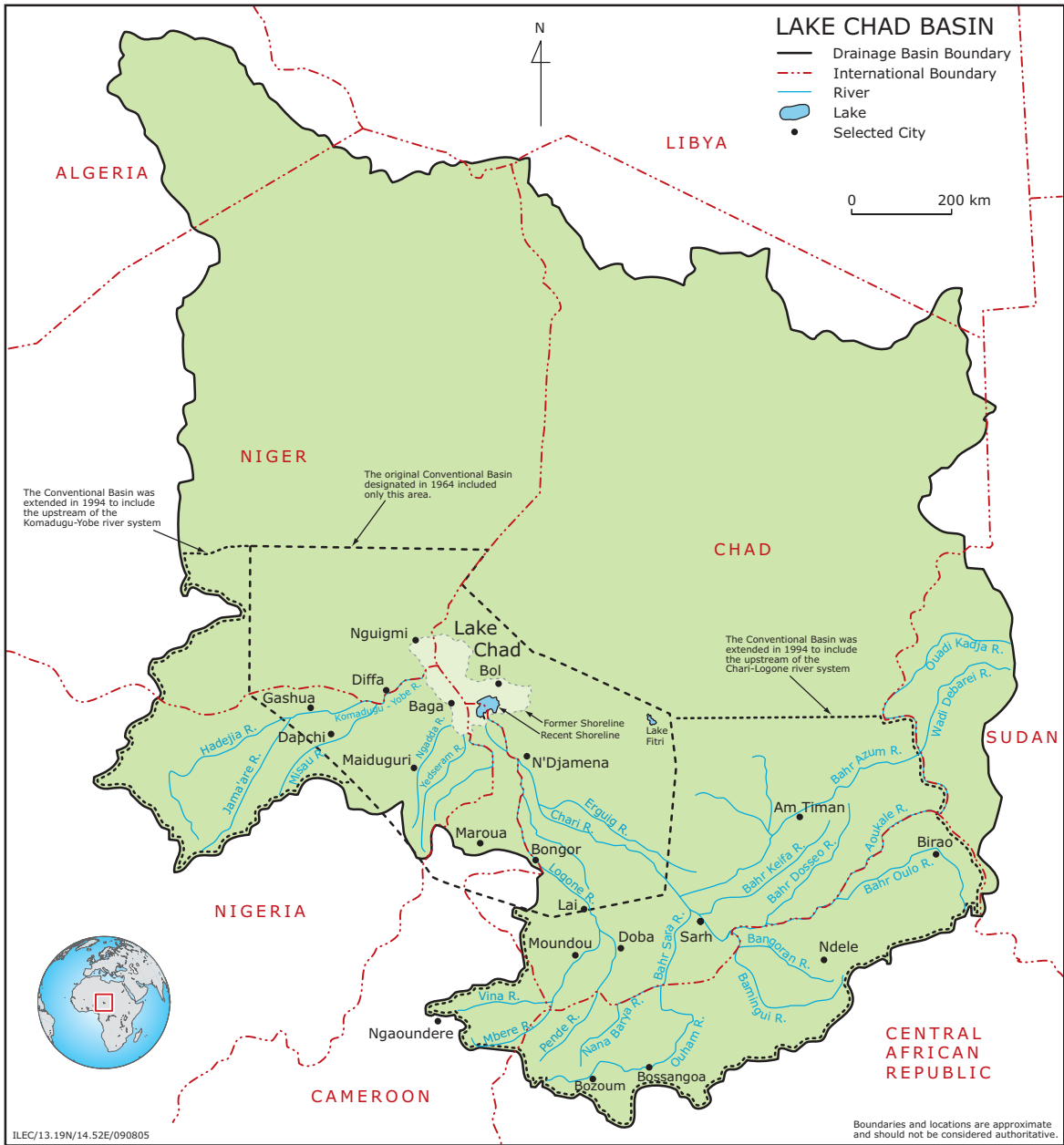


Figure A.5: Water resources of Lake Chad
(Source: Odada, 2005)

Appendix B: 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 $i = \{A, B\}$ and $\alpha^A + \alpha^B = 1$. 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 $Q = Q^A + Q^B$.

B.1 Industry Equilibrium

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

$$\max_{q_j^i \geq 0} \pi_j^i = (a - q_j^i - Q_{-j}^i - Q^l) q_j^i - (c^i + \tau^i) q_j^i, \quad (12)$$

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

Lemma B.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 Pigouvian tax will reduce the equilibrium output of the domestic producers and raise the output of the foreign rivals, other things being equal.

B.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 B.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 (5), except for the producer surplus, which is obtained using Equation (12), and consumer surplus, which is now expressed as $CS^i = \alpha^i CS = \frac{\alpha^i}{2} (q_j^i + Q_{-j}^i + Q^l)^2$.

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

$$\tau^{i,NC} = \frac{z^i(n^i+n^l)(1+d^i)}{n^i(n^i+n^l)} - \frac{n^i(a-c^i) - z^i(1+d^i) + n^l(a-c^l) - z^l(1+d^l)}{n^i(n^i+n^l)} \alpha^i, \quad (13)$$

which yields an equilibrium output of

$$q_j^{i,NC} = \frac{n^i n^l (c^l - c^i) - n^l z^i (1 + d^i) + n^i z^l (1 + d^l)}{n^i (n^i + n^l)} + \frac{n^i (a - c^i) - z^i (1 + d^i) + n^l (a - c^l) - z^l (1 + d^l)}{n^i (n^i + n^l)} \alpha^i \quad (14)$$

for every firm j .

Similar to autarky, Pigouvian 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, $\frac{\partial q_j^{i,NC}}{\partial z^i} = -\frac{(n^l+\alpha^i)(1+d^i)}{n^i(n^i+n^l)} < 0$ and $\frac{\partial q_j^{i,NC}}{\partial d^i} = -\frac{(n^l+\alpha^i)z^i}{n^i(n^i+n^l)} < 0$. 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 : $\frac{\partial \tau^{i,NC}}{\partial z^l} = \frac{\alpha^i(1+d^l)}{n^i(n^i+n^l)} > 0$, $\frac{\partial \tau^{i,NC}}{\partial d^l} = \frac{\alpha^i z^l}{n^i(n^i+n^l)} > 0$, $\frac{\partial q_j^{i,NC}}{\partial z^l} = \frac{(n^i-\alpha^i)(1+d^l)}{n^i(n^i+n^l)} > 0$, and $\frac{\partial q_j^{i,NC}}{\partial d^l} = \frac{(n^i-\alpha^i)z^l}{n^i(n^i+n^l)} > 0$. 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 Pigouvian policy on its industries (since $\frac{\partial \tau^{i,NC}}{\partial z^l} > 0$ and $\frac{\partial \tau^{i,NC}}{\partial d^l} > 0$), 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 $\frac{\partial q_j^{i,NC}}{\partial z^l} > 0$ and $\frac{\partial q_j^{i,NC}}{\partial d^l} > 0$). 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 Pigouvian 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 B.2. *Under cooperative (C) regulation, the joint welfare maximum is characterized as follows:*

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

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

As depicted in Figure B.1, when the appropriation rate in country i is relatively low ($z^i < \bar{z}$), 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 ($z^i > \bar{z}$), 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.

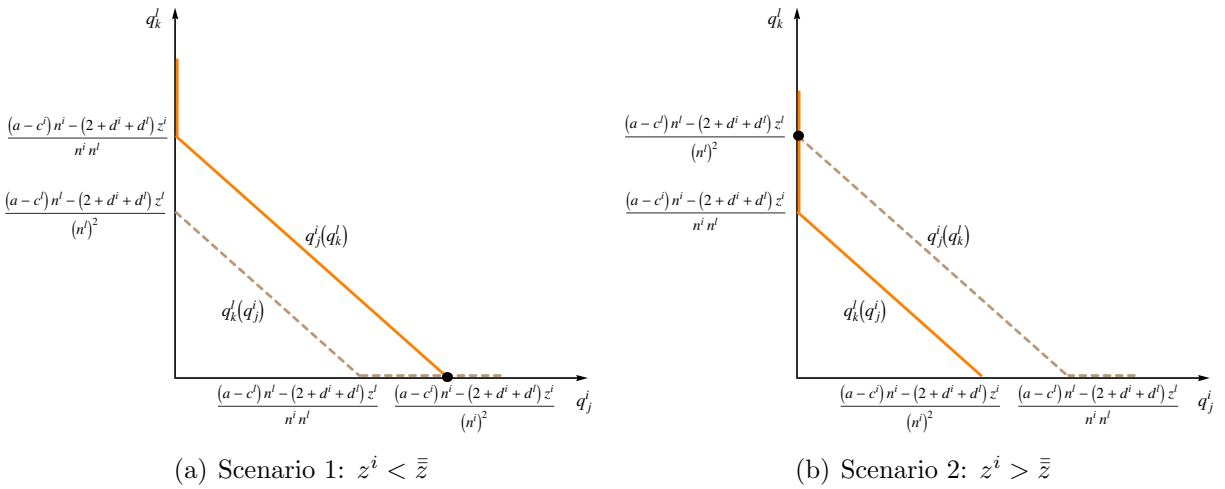


Figure B.1: Socially optimal cooperative firm output levels

B.3 Profit Comparison

Proposition B.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

$$\bar{z}_6 \equiv \frac{[n^i(a-c^i) + n^l(a-c^l)][(1+n^i+n^l)\alpha^i - n^i]}{(1+d^i)(1+n^i+n^l)(n^l+\alpha^i)} + \frac{(1+d^l)(n^i-\alpha^i)}{(1+d^i)(n^l+\alpha^i)} z^l \quad (15)$$

$$\bar{z}_7 \equiv \frac{[n^i(a-c^i) + n^l(a-c^l)][(1+n^i+n^l)\alpha^i + n^i]}{(1+d^i)(1+n^i+n^l)(n^l+\alpha^i)} + \frac{2n^i n^l (c^l - c^i)}{(1+d^i)(n^l+\alpha^i)} + \frac{(1+d^l)(n^i-\alpha^i)}{(1+d^i)(n^l+\alpha^i)} z^l \quad (16)$$

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 $z^i < \bar{z}$ (i.e., Scenario 1 in Proposition B.2), and thus only firms in country i produce positive amount, whilst those in country l remain inactive.

Proposition B.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:*

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

where

$$\bar{D}_1 \equiv \frac{[a + c^i n^i - c^l(1 + n^i)](1 + n^l)n^l}{(n^i + n^l + 1)z^l} - 2, \quad (17)$$

$$\bar{D}_2 \equiv \frac{[a - c^i n^i - c^l(1 + n^i)](1 + n^l)n^l + (a - n^l c^l)2n^i n^l}{(n^i + n^l + 1)z^l} - 2, \quad (18)$$

$$\bar{z}_8 \equiv \frac{n^i[(a - c^i)(1 + n^l) + n^i n^l(c^i - c^l)]}{(n^i + n^l + 1)(2 + d^i + d^l)}, \quad (19)$$

$$\bar{z}_9 \equiv \frac{n^i[(a - c^i)(1 + n^l + 2n^i) - n^i n^l(c^i - c^l)]}{(n^i + n^l + 1)(2 + d^i + d^l)}. \quad (20)$$

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 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 $CS^{i,U} = \frac{1}{2} (Q^{i,U})^2$. The residual amount of the CPR is $Y^U = \bar{Y} - z^A Q^{A,U} - z^B Q^{B,U}$ with the total environmental damage of $E^{i,U} = d^i (z^i Q^{i,U} + z^l Q^{l,U})$. 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 Pigouvian 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

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

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

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

Otherwise, the optimal policy is a subsidy, i.e., $\tau^{i,NC} < 0$. Also, it can be shown that

$$\frac{\partial \bar{z}_1}{\partial d^i} = -\frac{n^i(a^i - c^i)}{(n^i+1)(1+d^i)^2} < 0. \quad \blacksquare$$

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 Pigouvian 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

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

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

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

Otherwise, the optimal policy is a subsidy, i.e., $\tau^{i,C} < 0$. 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 Pigouvian 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 $q_j^{i,U} - q_j^{i,NC} > 0 \implies q_j^{i,U} > q_j^{i,NC}$ 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 $q_j^{i,U} - q_j^{i,C} > 0 \implies q_j^{i,U} > q_j^{i,C}$ 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 $\frac{\partial(q_j^{i,U} - q_j^{i,C})}{\partial d^i} = \frac{\partial(q_j^{i,U} - q_j^{i,C})}{\partial d^i} = \frac{z^i}{(n^i)^2} > 0$. Finally, it can be shown that

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

where $q_j^{i,NC} - q_j^{i,C} > 0 \implies q_j^{i,NC} > q_j^{i,C}$ 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., $\left(\frac{a^i - c^i}{n^i + 1}\right)^2 - \frac{(n^i(a^i - c^i) - z^i(1+d^i))^2}{(n^i)^4} > 0$, holds if and only if the appropriation rate satisfies

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

Otherwise, the equilibrium profits satisfy $\pi_j^{i,U} - \pi_j^{i,NC} < 0$. 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., $\left(\frac{a^i - c^i}{n^i + 1}\right)^2 - \frac{(n^i(a^i - c^i) - z^i(2+d^i+d^l))^2}{(n^i)^4} > 0$, holds if and only if the appropriation rate satisfies

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

Otherwise, the equilibrium profits satisfy $\pi_j^{i,U} - \pi_j^{i,C} < 0$. 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 $d^i > \frac{1+d^l}{2n^i} - 1 \equiv \bar{d}$. Otherwise, $\bar{z}_4 < \bar{z}_1$. ■

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., $\frac{(n^i(a^i-c^i)-z^i(1+d^i))^2}{(n^i)^4} - \frac{(n^i(a^i-c^i)-z^i(2+d^i+d^l))^2}{(n^i)^4} > 0$, holds if and only if the appropriation rate satisfies

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

Otherwise, the equilibrium profits satisfy $\pi_j^{i,NC} - \pi_j^{i,C} < 0$. 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 $d^i < \bar{d}$. Otherwise, $\bar{z}_5 < \bar{z}_4$. 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 $d^i < \bar{d}$. Otherwise, $\bar{z}_5 > \bar{z}_1$. Hence, cutoff \bar{z}_5 is bounded between \bar{z}_1 and \bar{z}_4 , i.e., $\min\{\bar{z}_1, \bar{z}_4\} < \bar{z}_5 < \max\{\bar{z}_1, \bar{z}_4\}$. ■

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

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

while under cooperative setting it is

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

where SW^i and SW^l , for $i, l = \{A, B\}$ and $i \neq l$, 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

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

Furthermore, profits under non-cooperative and cooperative regulation satisfy

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

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

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

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

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

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 $\pi_j^{i,U}(d^l = 0) > \pi_j^{i,C}(d^l = 0)$.

In particular,

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

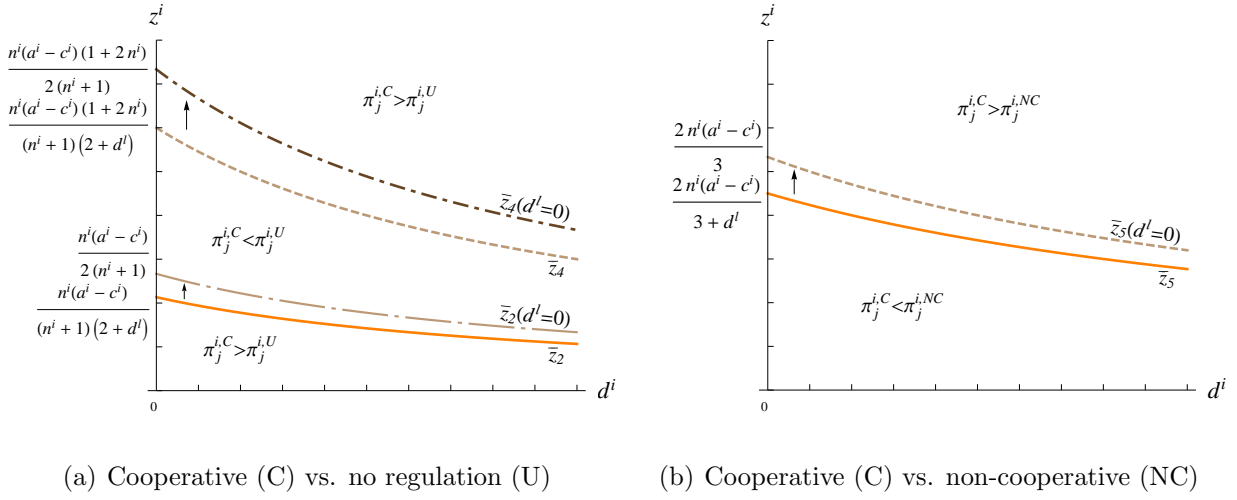


Figure C.1: Firm preferences for different regulatory settings, $d^l = 0$

and

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

Then, the difference of the above two quantities yields

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

Hence, $R(\pi_j^{i,U} > \pi_j^{i,C}) < R(\pi_j^{i,U}(d^l = 0) > \pi_j^{i,C}(d^l = 0))$, 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

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

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 Lemma B.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 B.2

Sketch of proof: Follow the same steps as in the proof of Lemma 2, 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 Proposition B.1

Sketch of proof: Follow the same steps as in the proof of Proposition 1, using the inverse demand function $p = a - Q$, where $Q = Q^i + Q^l = \sum_j^{n^i} q_j^i + \sum_k^{n^l} q_k^l$, and consumer surplus given by $CS^i = \alpha^i CS = \frac{\alpha^i}{2} (q_j^i + Q_{-j}^i + Q^l)^2$, for $i = \{A, B\}$ and $\alpha^A + \alpha^B = 1$. ■

Proof of Proposition B.2

Sketch of proof: Follow the same steps as in the proof of Proposition 2, using the inverse demand function $p = a - Q$, where $Q = Q^i + Q^l = \sum_j^{n^i} q_j^i + \sum_k^{n^l} q_k^l$, and consumer surplus given by $CS^i = \alpha^i CS = \frac{\alpha^i}{2} (q_j^i + Q_{-j}^i + Q^l)^2$, for $i = \{A, B\}$ and $\alpha^A + \alpha^B = 1$. ■

Proof of Proposition B.3

Sketch of proof: Follow the same steps as in the proof of Proposition 3, using the inverse demand function $p = a - Q$, where $Q = Q^i + Q^l = \sum_j^{n^i} q_j^i + \sum_k^{n^l} q_k^l$, and consumer surplus given by $CS^i = \alpha^i CS = \frac{\alpha^i}{2} (q_j^i + Q_{-j}^i + Q^l)^2$, for $i = \{A, B\}$ and $\alpha^A + \alpha^B = 1$. ■

Proof of Proposition B.4

Sketch of proof: Follow the same steps as in the proof of Proposition 4, using the inverse demand function $p = a - Q$, where $Q = Q^i + Q^l = \sum_j^{n^i} q_j^i + \sum_k^{n^l} q_k^l$, and consumer surplus given by $CS^i = \alpha^i CS = \frac{\alpha^i}{2} (q_j^i + Q_{-j}^i + Q^l)^2$, for $i = \{A, B\}$ and $\alpha^A + \alpha^B = 1$. ■

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