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## Pricing pollution in a non-cooperative world<sup>☆</sup>

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### ABSTRACT

I examine a policy-making game among countries that must choose both a policy instrument (e.g., a tax or a quota) and its intensity (i.e., the tax rate or the quota level) to price pollution. When countries price pollution non-cooperatively, they not only set the intensity inefficiently, they are also likely to adopt Pigouvian fees, despite quotas being better from a welfare perspective. Adopting a Pigouvian fee to address a multi-country externality generates a risk externality, and in some cases non-cooperatively chosen quotas can generate higher social welfare than maximum social welfare Pigouvian fees can deliver.

### 1. Introduction

Global public goods improve humanity's welfare and sustain the planet's long-term health. These goods help nations address problems such as the spread infectious diseases, the proliferation of weapons of mass destruction, and the rise in climatic changes. Despite their indispensability, such goods are undersupplied (Barrett, 2007; Nordhaus, 2019; Stiglitz, 2019). What is the best way to enhance the supply of global public goods and minimize inefficiencies? The answer to this question not only shapes humanity's welfare in our time, but it also has substantial ramifications for the welfare of future generations.

While the following analysis applies to most global public goods, let me focus on an example of addressing a global pollution problem to fix ideas. A century of economic research since Pigou (1920) suggests that pricing pollution is the best way to ensure efficiency. Subsequent

research has established that economic instruments (i.e., the price instrument and the quantity instrument), while being superior to other ways of pricing, are equivalent under complete information.<sup>2</sup> However, the consequences of incomplete information remained unclear until Weitzman (1974).

Weitzman (1974) lays the intellectual foundation for considering alternative ways of pricing pollution when knowledge is incomplete. A sensible policy raises pollution abatement considering both the benefit and the cost of abatement. Weitzman shows that a Pigouvian fee is less efficient than a cap-and-trade scheme when the slope of the marginal abatement cost function is small relative to the slope of the marginal abatement benefit function. The converse is also true. Nordhaus (2006), Sterner and Coria (2012), Goulder and Schein (2013), and Stavins (2020) summarize the literature about the pros and cons of adopting different policy instruments for pricing pollution. However, the

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<sup>2</sup> I use a pollution tax or Pigouvian fee as synonyms for the price instrument and a quota or a cap-and-trade scheme for the quantity instrument.

consequences of national sovereignty and the potential inefficiency arising from countries choosing policy instruments non-cooperatively have been absent in the literature.

A setting in which the provision of a global public good requires cooperation by multiple decisionmakers arises naturally. The setting arises due to the international law of national sovereignty enshrined in the 1648 Treaty of Westphalia and the 1969 Treaty of Vienna (Nordhaus, 2015, p. 1340). Because of that, this paper examines the efficiency implications of national sovereignty in choosing a pollution pricing instrument.

The main contribution of this paper is to show the general insight that *adopting a Pigouvian fee to address an externality, in a multi-decisionmaker setting with incomplete information, generates its own negative externality*. I refer to the inefficiency arising from a Pigouvian fee's negative externality as the *PvQ inefficiency*. If this inefficiency is high, even non-cooperatively chosen quotas can generate higher social welfare than the maximum possible social welfare from adopting Pigouvian fees.

A simple way to illustrate the origin of the PvQ inefficiency is to generalize Weitzman's workhorse model to a policy-making game involving multiple countries. Thus, a country benefits from the global supply of a public good and incurs a private cost of contributing to the global supply. When setting policies, a country's regulator does not foresee the technological opportunities or challenges firms face to comply with the regulation. And, countries choose both the type and intensity of a policy in a strategic setting facing technological uncertainty. The analysis of the game formalizes the presence of a novel source of policy inefficiency – a risk externality. This inefficiency arises as a result of a country choosing a policy instrument that imposes a negative externality on other countries. Thus, environmental policy can be inefficient due to the *intensity inefficiency* (i.e., the inefficiency arising when a country imposes a lower tax level or a higher pollution quota than the socially optimal, in the utilitarian sense) or the *PvQ inefficiency*.

To establish the PvQ inefficiency in a general setting, the first result I discuss examines the PvQ inefficiency when countries commit to any comparable policy intensities, including the socially optimal or the equilibrium policy intensities. To understand the incentives behind the inefficiency, suppose a country prefers the price instrument. A country prefers the price instrument to let firms operating in its jurisdiction benefit from the flexibility to respond to shocks and deliver a higher abatement level when they face a low abatement cost, or a lower abatement level when they face a high abatement cost. However, this flexibility introduces variability in the country's abatement level. This variability, in turn, generates a cross-country risk externality since other countries would pay a positive risk premium to avoid this variability. When choosing the price instrument, a country considers only its own benefit from cost reductions and ignores the externality it imposes on other countries. A country's risk externality increases with the number of countries exposed to it, and when the global risk premium is too high, adopting a quota instead becomes cooperatively more efficient than adopting the price instrument.

If the cost shock is global (e.g., the great recession in 2008), both the cooperatively more efficient and the equilibrium policy instruments exhibit asymmetry. This result contrasts with the symmetric choice of policy instruments under independent shocks. With a global shock, a country's optimal policy instrument becomes strictly strategic and depends on the policy instruments adopted by other countries. With independent shocks, a country's optimal policy instrument is strategically independent of the policy instruments of other countries. In addition, a global cost shock provides an efficiency-based explanation as to why a union of sovereign states often chooses the quantity instrument instead of the price instrument. For global Pigouvian fees to be cooperatively more efficient for  $n$  symmetric countries facing a global cost shock than a collection of national cap-and-trade schemes, the slope of the marginal abatement cost function has to exceed the slope of the marginal benefit function by an order of  $2n^2$ .

How significant can the PvQ inefficiency be? In the presence of the PvQ inefficiency, the supply of a multilateral public good suffers from an extra source of policy distortion. Since the PvQ inefficiency and the intensity inefficiency are distinct and can arise independently, the next result I discuss establishes the importance of the PvQ inefficiency by comparing its distortion with the distortion from intensity, for a general correlation structure of shocks. Strikingly, there exists a condition under which non-cooperatively chosen quotas result in higher collective welfare than taxes chosen to maximize social welfare. What is the underlying model behind these results?

## 2. Basic model

Suppose  $N \equiv \{1, 2, \dots, n\}$  is the set of countries indexed by  $i = 1, 2, \dots, n$ .<sup>3</sup> A country benefits from the total abatement of  $Q \equiv \sum_{j \in N} q_j$  and incurs a private cost  $C_i(q_i; \theta_i)$  from abatement of  $q_i$  made by firms operating in its jurisdiction. The reduced-form shock to cost,  $\theta_i$ , is drawn from a distribution with bounded support having a zero mean,  $\mathbb{E}[\theta_i] = 0$ , and a positive variance  $\sigma_i^2$ . From the viewpoint of country  $i$ 's regulator, the net benefit from abatement is

$$W^i \equiv B(Q) - C_i(q_i; \theta_i), \quad (1)$$

where  $B''(\cdot) < 0 < B'(\cdot)$  for all  $Q \geq 0$ ,  $\frac{\partial}{\partial q_i} C_i(q_i; \theta_i) \equiv C'_i(q_i; \theta_i) > 0$ , and  $\frac{\partial^2}{\partial q_i^2} C_i(q_i; \theta_i) \equiv C''_i(q_i; \theta_i) > 0$  for all  $q_i \geq 0$  and  $i \in N$ .<sup>4</sup>

**Remark 1.** Note that (1) allows for heterogeneity in size among countries. Thus, country  $i$ 's business as usual emissions is higher than country  $j$ 's if  $C'_i(0; 0) > C'_j(0; 0)$  even when  $C''_i(q_i; 0) = C''_j(q_j; 0) = C''(q_i; 0) \forall i, j \in N$ .

First, a decision-maker in each country chooses the type of policy  $T_i \in \{\tau, TP\}$ , where abatement is priced through the price (tax) instrument  $\tau$  or through the quantity (tradable permit) instrument  $TP$ . Let  $\mathbf{T} \equiv (T_1, \dots, T_n)$  be the vector of the type of policy instruments countries choose. Without loss of generality, unless otherwise stated, suppose the set  $M$  contains  $m$  countries with the price instrument  $T_i = \tau$ , and the set  $R \equiv N - M$  contains the remaining  $n - m$  countries with the quantity instrument  $T_i = TP$  at the first stage.

Second, after having observed the chosen profile of types  $\mathbf{T}$ , countries simultaneously choose the intensity  $I_i \in \{t_i, \kappa_i\}$ , where a tax level  $t_i \in \mathbb{R}_+$  whenever pollution is priced using the price instrument and similarly a tradable quota level  $\kappa_i \in \mathbb{R}_+$  whenever pollution is priced using the quantity instrument. Let  $\mathbf{I} \equiv (I_1, \dots, I_n)$ .

Policy choices in both stages are made under informational constraints. More precisely, decision-makers in each country act without knowing the realization of the random variables beforehand, except knowing the distribution. This assumption captures the notion that a regulator, when committing to a policy, does not have the same information as individuals regarding the available abatement options for each firm. Going forward, I maintain the assumption in Weitzman (1974) that the cost shocks are non-verifiable, and thus non-contractible.<sup>5</sup>

<sup>3</sup> There is a similar approach that starts with one region and splits it up into smaller regions. Weitzman (1974) used this approach in a single policymaker environment. However, I follow the conventional approach of using a country as a unit of analysis as in Alesina et al. (2005), Barrett (2007), and Harstad (2012). Besides, in a recent work, Karp (2020) adopts the approach in Weitzman (1974) and confirms the qualitative insights reported here are robust.

<sup>4</sup> A notation with the subscript  $-i$  is used with the conventional meaning – a vector with the subscript  $-i$  denotes the same vector with its  $i^{\text{th}}$  component removed.

<sup>5</sup> For example, in 2005 when the EU was setting up abatement goals for 2020, it could not know and contract on the fact that the great recession would occur in 2008 and reduce abatement costs. However, if shocks are verifiable, then regulators can implement mechanisms along the lines in Dasgupta et al. (1980) and raise efficiency.

Once policymakers have committed to the type **T** and the intensity **I** of policy instruments, the values of shocks in each country are realized. The realized values determine how much it costs firms to comply with a regulatory constraint. At the final stage, firms in each country choose the abatement level  $q_i$ , where  $\mathbf{q} \equiv (q_1, \dots, q_n)$ , conditional on the regulatory instrument in place and on the realization of the shocks.<sup>6</sup>

Since the intensity of a given policy instrument can take any non-negative value, identifying a more efficient policy instrument requires comparing equivalent policy intensities. The basis for comparison can be equivalence in expected abatement or expected marginal abatement cost.

**Comparability.** A price instrument with intensity  $\hat{t}_i$  is comparable to a quantity instrument with intensity  $\hat{\kappa}_i$  in pricing pollution if and only if

$$\mathbb{E}_{\theta_i} [q_i(\hat{t}_i; \theta_i)] = q_i(\hat{\kappa}_i; \theta_i) \text{ and } \hat{t}_i = \frac{\partial}{\partial q_i} \mathbb{E}_{\theta_i} [C_i(q_i(\hat{\kappa}_i; \theta_i); \theta_i)] \quad (2)$$

I focus on the pure-strategy (subgame-perfect) equilibrium. A pure-strategy equilibrium is a configuration  $(\mathbf{T}^*, \mathbf{I}^*, \mathbf{q}^*)$ , where a country's policy instrument  $T_i^* \in \{\tau, TP\}$ , its intensity  $I_i^* : T_i \rightarrow \mathbb{R}_+$ , and abatement  $q_i^* : T_i \times I_i \rightarrow \mathbb{R}_+$  such that  $(\mathbf{T}, \mathbf{I})$  is the strategy of policymakers and  $\mathbf{q}$  is the strategy of firms, abatement is the best response to the type and intensity of a policy instrument, and the type and intensity of a policy instrument are the best responses to abatement. The superscript **\*\*** is used to designate the cooperatively more efficient policy instrument (or cooperatively optimal policy intensity), and the superscript **\*** is used to designate choices in equilibrium, in the remainder of the text.

### 3. An inefficiency result

Let me start with a general result of inefficiency. For any comparable policy intensities, countries tend to choose the price instrument even if it is cooperatively less efficient than the quantity instrument.

**Proposition 1.** For any comparable policy intensities  $\{\hat{t}_i, \hat{\kappa}_i\}$ , country *i* benefits from choosing  $T_i = \tau t$  even if it is cooperatively less efficient than choosing  $T_i = TP$  whenever

$$\frac{\sigma_{\sum_{M \cup \{i\}} q_j(\hat{t}_j; \theta_j)}^2 - \sigma_{\sum_M q_j(\hat{t}_j; \theta_j)}^2}{\sigma_{q_i(\hat{t}_i; \theta_i)}^2} \leq \frac{C_i''(\mathbb{E}q_i(\hat{t}_i; \theta_i))}{|B''(\hat{Q})|} \leq \frac{n\sigma_{\sum_{M \cup \{i\}} q_j(\hat{\kappa}_j; \theta_j)}^2 - n\sigma_{\sum_M q_j(\hat{\kappa}_j; \theta_j)}^2}{\sigma_{q_i(\hat{\kappa}_i; \theta_i)}^2},$$

where  $\hat{Q} = \sum_N q_j(\hat{\kappa}_j; \theta_j)$  and  $\sigma_X^2 = \mathbb{E}[X - \mathbb{E}[X]]^2$ .

**Proof.** see Appendix.

Thus, countries tend to choose the price instrument even when it is cooperatively less efficient than the quantity instrument because the price instrument's cost-savings are captured privately and its risk premium is borne globally. In the following sections, I assume that the benefit and cost functions are quadratic,

$$W^i = B'Q - B''Q^2/2 - [C' + \theta_i]q_i - C''q_i^2/2, \quad (\text{W-A}) \quad (3)$$

with  $B', B'', C'$ , and  $C''$  being positive parameters. Weitzman (1974) establishes (3) as a second-order approximation of a general  $B(Q) - C_i(q_i; \theta_i)$  function.

<sup>6</sup> The timing in the model assumes that policymakers can commit on a choice of policy instrument in the entire period. In the contexts in which status quo bias and institutional and bureaucratic inertia sustain a chosen policy instrument, the assumption of commitment to a policy instrument is reasonable.

### 4. Analysis

To identify the equilibrium strategies, I first consider equilibrium strategies beginning with the final subgame, where a representative firm chooses abatement, and then work backward. Since firms operate in a regulatory space in which they are exposed to technology shocks, a firm's abatement is contingent on a technology shock and regulation. An optimal reaction function for firms is

$$q_i(\kappa_i; \theta_i) \equiv \arg \min_{q_i \geq \kappa_i} C_i(q_i; \theta_i) \quad (4)$$

when abatement is regulated using the quantity instrument or

$$q_i(t_i; \theta_i) \equiv \arg \min_{q_i \geq 0} \{C_i(q_i; \theta_i) - t_i q_i\} \quad (5)$$

when abatement is regulated using the price instrument.

With a cost function  $C_i(q_i; \theta_i)$ , the cost of abatement is zero when  $q_i = 0$  and the abatement costs increases in abatement. When facing regulation through a quota  $\kappa_i$ , firms comply with the regulation by minimizing the compliance costs subject to the constraint  $q_i \geq \kappa_i$ . Firms minimize abatement costs by choosing the minimum abatement  $q_i = \kappa_i$  and incurring ex-post abatement costs of  $C_i(q_i(\kappa_i; \theta_i); \theta_i)$ . Although firms minimize compliance costs, in being fixed ex-ante, a quota prohibits a country's abatement from responding to firms' ex-post marginal costs. Similarly, when facing regulation through a tax  $t_i$ , firms' optimal abatement  $q_i(t_i; \theta_i)$  balances marginal costs,  $\frac{\partial}{\partial q_i} C_i(q_i; \theta_i)$  with the marginal benefits  $t_i$ . The ex-post abatement cost when facing a tax becomes  $C_i(q_i(t_i; \theta_i); \theta_i)$ . Since firms know the realized value of cost shocks  $\theta_i$  before choosing abatement levels, a tax allows them to incorporate the extra information about shocks. Incorporating the extra information, in turn, lets a country's abatement respond to firms' ex-post marginal costs.

#### 4.1. The origin of environmental policy inefficiencies

In choosing efficient policies, the boundaries of sovereignty across countries are taken as fixed. At the stage of choosing policy intensities, the cooperatively best policy intensities  $\{t_i^{**}, \kappa_i^{**}\}_{i=1}^n$  for all countries maximize the collective welfare,  $\mathbb{E}[\sum_N W^i]$  taking into account firms' optimal reactions to the policy intensities, (4) and (5).

In a non-cooperative world of multiple nations, a country's decision-maker chooses a policy intensity  $t_i^*$  or  $\kappa_i^*$  in order to maximize the country's welfare  $\mathbb{E}[W^i]$ . This maximization anticipates that all countries choose a policy intensity and that firms react optimally in accordance with (4) or (5). After all countries adopt their own policy instruments, a country's decision-maker chooses a policy's intensity in order to maximize the country's welfare given firms' reactions to the chosen policy.

The cooperatively optimal intensity of price is  $t_i^{**} = \frac{(nB' - C')C'' + (n^2 B'' + C'')C'}{(nB' - C')C'' + (nB'' + C'')C'}$  whereas the equilibrium intensity of price is  $t_i^* = \frac{B''n^2 + C''}{(B' - C')C'' + (nB'' + C'')C'}$ ,  $\forall i \in M$ . And, the cooperatively optimal intensity of quantity is  $\kappa_i^{**} = \frac{nB' - C'}{n^2 B'' + C''}$  whereas the equilibrium intensity of quantity is  $\kappa_i^* = \frac{B' - C'}{nB'' + C''}$ ,  $\forall i \in R$ . There exists inefficiency in a policy intensity,  $t_i^* < t_i^{**}$  and  $\kappa_i^* < \kappa_i^{**}$ , whenever  $n > 1$ . Formally, the magnitude of the price instrument's intensity inefficiency is defined as:

$$IE_\tau(n) := \sum_N [\mathbb{E}W^i(q_i(t_i^{**}, \theta_i), q_{-i}(t_{-i}^{**}, \theta_{-i})) - \mathbb{E}W^i(q_i(t_i^*, \theta_i), q_{-i}(t_{-i}^*, \theta_{-i}))]. \quad (6)$$

The following Lemma establishes the welfare consequence of the intensity inefficiency from adopting the price instrument.

**Lemma 1.** The magnitude of the price instrument's intensity inefficiency  $IE_\tau(n)$  is given by

$$IE_\tau(n) = n \left[ \frac{n^2 B'' + C''}{2} \right] \left[ \frac{nB' - C'}{n^2 B'' + C''} - \frac{B' - C'}{nB'' + C''} \right]^2. \quad (7)$$

**Proof.** see Appendix.

The reason why individually optimal policy intensities are less than the cooperatively optimal levels is that decision-makers only consider their own country's interest and not the broader benefits of the policy for all countries.

4.1.1. The PvQ inefficiency

At the initial stage, all policymakers choose the best way of pricing pollution. Before proceeding further, it is worth noting that the equilibrium (or the cooperatively optimal) policy intensities are comparable.

**Remark 2.** For each country, both the best policy intensities  $\{t_i^{**}, \kappa_i^{**}\}_{i=1}^n$  and the equilibrium policy intensities  $\{t_i^*, \kappa_i^*\}_{i=1}^n$  are comparable.

The result that the cooperatively optimal policy intensities  $\{t_i^{**}, \kappa_i^{**}\}_{i=1}^n$  are comparable has an interesting implication. If the level of price or quantity a country implements is fixed at the cooperatively optimal level, does it price pollution more efficiently? While this thought experiment is unrealistic, it is worth knowing whether countries will price pollution efficiently.<sup>7</sup> Together with Proposition 1, Remark 2 implies that inefficiency arises from adopting the price instrument even when countries adopt the cooperatively optimal policy intensities.

What is the magnitude of the PvQ inefficiency? Formally, the PvQ inefficiency from  $m$  countries adopting the price instrument when adopting the quantity instrument is more efficient, is given by

$$PvQ(m) := \mathbb{E} \sum_{M \subset N} [W^i(q_i(\kappa_i^{**}, \theta_i), q_{-i}(\kappa_{-i}^{**}, \theta_{-i})) - W^i(q_i(t_i^{**}, \theta_i), q_{-i}(t_{-i}^{**}, \theta_{-i}))]. \tag{8}$$

A cooperatively more efficient policy instrument for each country maximizes the collective welfare while correctly anticipating that all countries implement the cooperatively optimal policy intensity and that firms react optimally in accordance with (4) or (5). The welfare loss from countries adopting the price instrument despite adopting the quantity instrument is cooperatively more efficient is given by the PvQ inefficiency.

**Proposition 2.** The magnitude of the PvQ inefficiency  $PvQ(m)$ , when  $m$  countries adopt the price instrument, is given by

$$PvQ(m) = \frac{nB'' \left[ \sum_M \sigma_i^2 + 2 \sum_{i=1}^{m-1} \sum_{j=i+1}^m \rho_{ij} \sigma_i \sigma_j \right] - C'' \sum_M \sigma_i^2}{2[C'']^2}, \tag{9}$$

where  $\rho_{ij}$  is the Pearson correlation coefficient for  $\theta_i$  and  $\theta_j$  for  $i \neq j$ .

**Proof.** see Appendix.

The two policy instruments are equally efficient and  $PvQ(m) = 0$  when policymakers know everything individual firms know. However, economic research since Hayek (1945) has questioned the realism of this assumption.

With differential information, the price instrument is more efficient if the preference for abatement risk is neutral – a positive cost-saving is obtained with zero risk premium. Risk neutrality is a valid assumption when the marginal environmental damage from an extra unit of pollution at low levels of pollution is exactly equal to the marginal environmental damage from an extra unit of pollution at high levels of pollution, which is not the case for most environmental problems. As Pindyck (2007, p. 47) writes, “environmental cost and benefit functions tend to be highly nonlinear.” In fact, for most pollution problems,

<sup>7</sup> The thought experiment is the following: suppose a truly multinational and technocratic group of economists, say in the World Bank or the IMF, have calculated the cooperatively optimal tax or quota for each country, leaving the choice between the two instruments for countries. Could there be an avoidable inefficiency remaining if countries were to pick the tax or quota calculated for them by the impartial technocrats?

the preference for abatement risk is negative and the risks of crossing environmental thresholds are significant. With differential information, abatement risk aversion, and multiple countries, the risk externality arises. If  $C''/B'' > n \left[ 1 + 2 \left[ \sum_{i=1}^{n-1} \sum_{j=i+1}^n \rho_{ij} \sigma_i \sigma_j \right] / \sum_N \sigma_i^2 \right]$ , then cost-savings from regulatory flexibility dominate the risk premium. In this case, it is cooperatively more efficient for all countries to adopt Pigouvian fees. However, if  $C''/B'' < n \left[ 1 + 2 \left[ \sum_{i=1}^{n-1} \sum_{j=i+1}^n \rho_{ij} \sigma_i \sigma_j \right] / \sum_N \sigma_i^2 \right]$ , then it is cooperatively more efficient for all countries to adopt cap-and-trade systems due to excessive risk externality.<sup>8</sup>

The PvQ inefficiency in (9) depends upon the degree of correlation of shocks across countries, which can be independent and country-specific or global or perfectly correlated. In reality, the shocks can exist between the two extremes. To obtain sharp predictions, let us explore the two extreme cases in greater detail.

4.1.2. Consequences of a global shock

Arguably, we are living in a time when countries are going through extensive digital, financial, and commercial integration. Knowledge about abatement technologies invented in one place can flow quickly to other place, while a technology of generating pollution-free energy can make its way to other parts of the planet in a few months. To examine the consequences of deep technological interdependence, this section replaces the assumption of independent shocks with a global shock; that is,  $\theta_i = \theta$  and  $\sigma_i^2 = \delta^2, \forall i \in N$ .

With a global shock, the welfare loss from adopting the price instrument becomes  $PvQ(m) = \frac{mnmB'' - C''}{2C''^2} \delta^2$ , and the cooperatively optimal number of countries adopting the price instrument is the nearest integer to

$$m^{**} = \frac{1}{2n} \frac{C''}{B''}. \tag{10}$$

Note that (10) has a stark implication. In reality, the value of  $n$  is about 200 sovereign countries. Thus, for adopting taxes globally to become cooperatively more efficient than adopting cap-and-trade schemes for symmetric jurisdictions, the value of  $C''$  has to exceed the value of  $B''$  by the order of  $2n^2$ , which is 80,000.

**Lemma 2.** Suppose the cost shock is identical in all countries. Then  $m^{**}$  is the nearest integer to  $\frac{C''}{2nB''}$  whereas  $m^*$  is the nearest integer to  $\max\{0, \frac{C'' - B''}{2B''}\}$ .

**Proof.** Country  $i$ 's welfare difference from committing to the quantity instrument  $\kappa_i^*$  instead of committing to the price instrument  $t_i^*$  when all countries commit to the equilibrium amount of prices and quantities, is

$$\mathbb{E}W^i(q_i(\kappa_i^*; \theta), q_{-i}(t_{-i}^*; \theta_{-i})) - \mathbb{E}W^i(q_i(t_i^*; \theta), q_{-i}(t_{-i}^*; \theta_{-i})) = \frac{[2m + 1] B'' - C''}{2C''^2} \delta^2. \tag{11}$$

If a country expects that no other country will adopt the price instrument in equilibrium, (11) implies that a country benefits from committing to the price instrument only if  $B'' < C''$ . However, if a country expects that other countries will adopt the price instrument in equilibrium, (11) implies that a country benefits from committing to the price instrument only if  $B'' < \frac{C''}{2m+1}$ . In equilibrium, a country is

<sup>8</sup> Note that the inefficiency arises not from practical limitations of adopting a tax, such as the political difficulty of imposing a tax and changing it over time (Slemrod and Bakija, 2017), the ease of allowing exceptions and loopholes, the ease of being undermined through subsidies to complementary inputs, or countries with a weak fiscal capacity failing to enforce a tax and avoid evasion (e.g., Besley and Persson, 2009; Besley and Persson, 2011), etc. Since the analysis in this paper focuses on efficiency, considerations of distribution and practical issues similar to the ones mentioned above are outside the scope of this paper. For a more complete coverage of other issues in addition to efficiency, see Sterner and Coria (2012) and Stavins (2020).

indifferent between committing to the price instrument or the quantity instrument; thus the equilibrium  $m^*$  becomes the nearest integer to

$$m^* = \max \left\{ 0, \frac{C'' - B''}{2B''} \right\}. \tag{12}$$

In this particular case, a country having  $B'' = \frac{C''}{2m+1}$  is indifferent between adopting the price and the quantity instrument; hence, it has a mixed strategy whereas the remaining countries have a pure strategy of choosing either the price or the quantity instrument. If  $\frac{C''}{B''} = 2n + 1$ , then  $m^* = n$  and  $m^{**} \leq 2$ ; whereas if  $\frac{C''}{B''} \geq 2n^2$  for  $n > 1$ , then  $m^* = m^{**} = n$ .  $\square$

A global technology shock has numerous implications. First, with a global cost shock, the cooperatively more efficient policy instrument and an individual country's choice in equilibrium exhibit asymmetry – only some countries choose the price instrument despite all countries being identical in every respect. Second, with a global cost shock, the equilibrium number of countries adopting the quantity instrument is positive, despite  $C'' > B''$ . Third, having no country adopt the price instrument despite  $C'' > B''$  can be cooperatively more efficient if  $C'' < 4nB''$ .

#### 4.1.3. Consequences of independent shocks

If the cost shocks are country-specific and independent,  $\rho_{ij} = 0$ , the magnitude of the PvQ inefficiency takes a simple form,  $PvQ(m) = \frac{nB'' - C''}{2C''^2} \sum_{i=1}^m \sigma_i^2$ . When  $C'' > nB''$ , the policy distortion decreases in  $m$  and all countries choosing the price instrument is Pareto inefficient.

**Lemma 3.** *At the equilibrium levels of policy intensities, there exists a PvQ inefficiency if  $1 < \frac{C''}{B''} < n$ .*

**Proof.** To find the equilibrium, continue assuming  $m$  countries have committed to the price instrument at the first stage. Also assume that members of the set  $\bar{R} \equiv N - M - i$  of  $n - m - 1$  countries have committed to the quantity instrument at the first stage. Country  $i$ 's welfare gain from committing to the price instrument instead of the quantity instrument is

$$\mathbb{E}W^i(q_i(t_i^*; \theta_i), q_{-i}(I_{-i}^*; \theta_{-i})) - \mathbb{E}W^i(q_i(\kappa_i^*; \theta_i), q_{-i}(I_{-i}^*, \theta_{-i})) = \frac{C'' - B''}{2C''^2} \sigma_i^2. \tag{13}$$

Note that the result in (13) follows from the main Proposition in Mideksa and Weitzman (2019). In sum, on the equilibrium profile of abatement, country  $i$  obtains higher welfare from committing to the price instrument if  $C'' > B''$ , but a country's choice of the price instrument is inefficient whenever  $1 < \frac{C''}{B''} < n$ .  $\square$

#### 4.2. The significance of the PvQ inefficiency

As noted earlier, there are two potential sources of policy distortion when countries non-cooperatively choose both their policy instrument and policy intensity. Countries may adopt the cooperatively more efficient policy instruments but inefficient intensities or cooperatively less efficient policy instruments but cooperatively optimal intensities. Or a country may have both a policy instrument and a policy intensity inefficient. To evaluate the significance of the PvQ inefficiency, one can compare the welfare losses from these two sources of inefficiency and ask – under which conditions does the collective welfare from non-cooperatively determined emissions quotas exceed the maximum welfare that can be obtained from taxes?

**Proposition 3.** *The social welfare from the non-cooperatively chosen quantity intensities is higher than the social welfare from the cooperatively*

*optimal price intensities (i) when the cost shocks are identically and independently distributed across all countries if  $\mu_{iid}(n) > 1/\sigma^2$ , (ii) when the cost shock is identical across all countries if  $\frac{nB'' - C''}{nB'' - C''} \mu_{iid} > 1/\delta^2$ , where*

$$\mu_{iid}(n) \equiv \frac{[nB'' - C'']}{[n^2B'' + C''] [C'']^2} \left[ \frac{nB' - C'}{n^2B' + C'} - \frac{B' - C'}{nB' + C'} \right]^{-2}.$$

**Proof.** see Appendix.

To interpret the result, note that  $\sigma^2$  measures the degree of information differential between regulators setting policies and individual firms deciding the amount of emissions to reduce. When  $\sigma^2$  (or  $\delta^2$ )  $\rightarrow 0$ , regulators not only know as much as individuals regarding the available abatement options but can also correctly anticipate shocks such as the great recession before they occur. However, if the information differential between regulators and individual firms is large and  $\sigma^2$  (or  $\delta^2$ )  $\rightarrow \infty$ , the sufficient condition for the result is easily satisfied.

The result that the welfare from non-cooperatively determined quotas can exceed the maximum welfare from adopting Pigouvian fees may appear counter-intuitive at first glance. However, the economics is straightforward. All else being equal, a country's optimal policy instrument balances the trade-off between the flexibility to take advantage of cost-reducing shocks and the risk that abatement will be too low or too high ex post. A fixed quantity is inflexible and does not allow a country to benefit from cost-reducing shocks, yet it avoids the risk premium from variable abatement. The price instrument, in contrast, allows a country to benefit from socially useful cost-reducing shocks, yet it imposes the risk that abatement will be too low or too high ex post. Thus, it is rational for a country to choose the price instrument only if the benefit from private cost savings exceeds the private risk premium. However, adopting the price instrument is cooperatively more efficient only if the social cost saving for each unit of abatement is greater than the social risk premium from having a too loose or too tight policy ex post. The misalignment between the private and social costs highlights the risk externality arising from using the price instrument. When a country uses the price instrument, it benefits from the cost savings, but the risk externality to other countries can be too high. When countries adopt the cooperatively optimal intensity of the price instrument, each country imposes risk externalities upon the rest. In this case, these countries are better off with non-cooperatively determined and inefficiently low quotas. For this reason, an analysis ignoring the fact that more than 200 sovereign nations can have a non-zero value for risk and insurance provides a misleading answer. Of course, welfare can increase if countries adopt cooperatively optimal intensities of the quantity instrument.

The result in Proposition 3 relates to large body of research in international macroeconomics, building upon Rogoff (1985), van der Ploeg (1988), and Kehoe (1989). It identifies an inefficiency similar to those arising due to the credibility problem, which induces cooperative policies to backfire and reduce welfare. Rogoff (1985) and van der Ploeg (1988) investigate the inefficiency in monetary policy coordination. Similarly, Kehoe (1989) examines the inefficiency in fiscal policy coordination.

Note that the discussion so far has focused on a pure price or quantity instrument. Dasgupta and Heal (1979) have shown that mixed instruments (i.e., non-linear taxes or taxes with emissions caps and floors) are more efficient than an extreme linear carbon tax or a cap and trade. While non-linear prices can limit price variations and the risk externality, they are often hard to implement in reality when the shocks are hard to anticipate at the time of policy design. Thus, I focus on the extreme instruments for consistency with the literature. Besides, the extreme cases are thought to be simpler to communicate to policy makers than the mixed instruments.

### 5. Consequences of different functional forms

The choice of quadratic benefit and cost functions is strategic. It allows for mean–variance decomposition for any type of shocks. Does the core insight carry through other utility functions? The assumption of a quadratic cost function is crucial for a tractable way of presenting the benefits of Pigouvian fee’s flexibility,

$$F := \mathbb{E} [C_i (q_i (t_i) ; \theta_i)] - \mathbb{E} [C_i (q_i = \kappa_i ; \theta_i)] = \sigma^2 / 2C'' ,$$

for any iid shocks with  $\mathbb{E} [\theta_i] = 0$  and  $\mathbb{E} [\theta_i^2] = \sigma^2$ . In addition to tractability, there are issues about the existence of the expected value that I will discuss below.

To identify the more efficient policy instrument, a regulator will compare this benefit from ex-post flexibility with the extra risk premium from adopting a Pigouvian fee. Let  $m - 1$  countries have adopted a Pigouvian fee and  $n - m$  countries have adopted a quota. If  $m$  countries choose a Pigouvian fee, a global abatement becomes  $Q(t, m) = \sum_M [t_i - C' - \theta_i] / C'' + \sum_{N-M} \kappa_i$ . For the benchmark with  $B(Q) := B'Q - B''Q^2/2$ , the extra risk premium is  $RP(B'', C'') \propto \mathbb{E}[B(Q(t, m - 1))] - \mathbb{E}[B(Q(t, m))] = B''\sigma^2/2 [C'']^2$ . This gives the well-known expression reflecting Weitzman’s profound insight:

$$F - RP(B'', C'') = \frac{C'' - B''}{2C''} \frac{\sigma^2}{C''} . \tag{WI-Q}$$

Weitzman’s insight in this specification has given rise to three core observations. First, if  $\sigma^2 \rightarrow 0$ , then both the benefit from the flexibility and the risk premium converge to zero. Second, when the preference for risk is neutral, the price instrument is more efficient. Third, when the risk aversion increases, the price instrument becomes less efficient. The literature has adopted a quadratic benefit function because it is tractable. Does the trade-off remain if we consider other standard utility functions (e.g., the CARA and CRRA)?

The analysis I sketch below suggests that the qualitative features of risk-flexibility trade-off and risk externality carry through the other standard benefit functions. However, tractability in a full-fledged analysis cannot be maintained, unless done numerically a point that I cover shortly. To sketch the argument, let us focus on another commonly used utility function, the constant absolute risk aversion (CARA) function with  $\lambda > 0$  as the coefficient of absolute risk aversion. With the CARA benefit function,

$$B(Q) := -e^{-\lambda Q} ,$$

the marginal benefit is positive and benefit is concave in  $Q$ . Unlike the quadratic benefit function, the CARA benefit function is truly non-linear and it has positive derivatives in the odd orders whereas negative derivatives in the even orders of differentiation. When a country chooses a Pigouvian fee, the expected benefit from abatement for the class of normally distributed shocks becomes

$$-\mathbb{E} [e^{-\lambda Q}] = -e^{-\lambda [\mathbb{E}[Q] - \lambda \sigma^2 / 2 [C'']^2]}$$

suggesting that the extra risk premium of  $\lambda \sigma^2 / 2 [C'']^2$ . The difference between the cost-saving from flexibility  $F$  and the risk premium  $RP(\lambda)$  from the price instrument becomes

$$F - RP(\lambda) = \frac{C'' - \lambda}{2C''} \frac{\sigma^2}{C''} . \tag{WI-CARA}$$

If  $\sigma^2 \rightarrow 0$ , then  $F - RP(\lambda) \rightarrow 0$  confirming the first insight above. Second, if the coefficient of absolute risk aversion takes a value of zero, then the price instrument is more efficient,  $F - RP(\lambda = 0) > 0$ . Third, when the risk aversion increases, the price instrument becomes less efficient (i.e.,  $\frac{\partial [F - RP(\lambda)]}{\partial \lambda} < 0$ ). These results suggest that the qualitative insights are preserved under the truly non-linear CARA utility function.

Similarly, one can consider a utility function with a constant relative risk aversion, CRRA function. For

$$B(Q) := \frac{1}{1 - \gamma} Q^{1 - \gamma}$$

with  $\gamma \neq 1$  and  $B(Q) = \ln(Q)$  with  $\gamma = 1$ , [Geweke \(2001\)](#) writes that “in a standard environment for choice under uncertainty with constant relative risk aversion (CRRA), the existence of expected utility is fragile with respect to changes in the distributions of random variables...” However, for the class of log-normally distributed shocks, the expectation exists and the extra risk premium is  $[\gamma - 1] \sigma^2 / 2 [C'']^2$ . Thus, the difference between the benefit from the flexibility and the risk premium is

$$F - RP(r) = \frac{1 + C'' - \gamma}{2C''} \frac{\sigma^2}{C''} . \tag{WI-CRRA}$$

If  $\sigma^2 \rightarrow 0$ , then  $F - RP(\gamma) \rightarrow 0$  confirming the first insight above. Second, if the coefficient of relative risk aversion takes a value of zero, then the price instrument is more efficient,  $F - RP(0) = \frac{1 + C''}{2C''} \frac{\sigma^2}{C''} > 0$ . Third, when the risk aversion increases, the price instrument becomes less efficient (i.e.,  $\frac{\partial [F - RP(\gamma)]}{\partial \gamma} < 0$ ). Thus, the qualitative insights are preserved under the other truly non-linear CRRA utility function.

#### Simulation for Proposition 3.

Since the analytical solution arises only in restrictive functional forms, it is necessary to see if the results hold under different functional forms. Table-1 presents an example of numerical analysis assuming different non-linear welfare functions, where:

- $X$  is utilitarian social welfare when all countries adopt taxes that maximize utilitarian social welfare.
- $Y$  is utilitarian social welfare when all countries adopt non-cooperatively determined quotas.

Assuming that the shocks are perfectly correlated across countries and drawn from a uniform distribution symmetric at zero. For example, the cell with  $(\beta, \sigma_\theta^2) = (2.25, 0.33)$  for  $\eta = 0.00$  focuses on the case in which the benefit function is logarithmic whereas the cost function is  $C(q_i; \theta_i) = [\gamma + \theta_i]q_i + \frac{\xi}{2}q_i^{2.25}$  in which the variance of  $\theta_i$  is 0.33. A cell reports a positive sign when the utilitarian social welfare that arises from cooperatively optimal taxes  $X$  is greater than the utilitarian social welfare from non-cooperatively chosen quotas  $Y$ , and a negative sign when  $X < Y$ .

Note that  $\lim_{\eta \rightarrow 0} B(Q) = \log(Q)$ . In the rows with  $\sigma = 0.00$ , there is incomplete information. In this case, taxes that maximize a utilitarian social welfare result in a higher utilitarian social welfare than non-cooperatively determined quotas. This is confirmed in the first three rows. However, under incomplete information (e.g., when  $\sigma = 0.33$  or  $\sigma = 1.33$ ), the opposite can be true, consistent with proposition 3. While [Proposition 3](#) depends on a quadratic model for tractability, the results in [Table 1](#) lend some support to the possibility that risk externality could be substantively important.

Taken together, how do the results developed so far advance the literature?

### 6. Contributions to the literature

The choice between price and quantity is a long-standing issue in different fields of economic research. To raise its profit, a firm in an oligopoly chooses to compete with its rivals either in quantity or in price ([Cournot, 1838](#); [Bertrand, 1883](#); [Tirole, 1988](#)). To raise revenue, while minimizing distortions in international trade, a revenue-constrained policymaker chooses between a tariff and a quota ([Bhagwati, 1968](#); [Dasgupta and Stiglitz, 1977](#)). To crack the glass ceiling problem for women, policymakers choose between a price incentive and a quota ([Chattopadhyay and Duflo, 2004](#); [Besley et al., 2017](#); [Bertrand et al., 2019](#)).

The contributions of this paper advance the literature explaining inefficient policies stemming from the limits of agency ([Alesina and Rodrik, 1994](#); [Besley, 2006](#); [Callander and Raiha, 2017](#)), the power of organized interest ([Buchanan and Tullock, 1975](#); [Grossman and Helpman, 1994](#); [Rodrik, 1995](#); [Aidt and Dutta, 2004](#)), and the problem

**Table 1**  
Numerical examples regarding the sign of  $X - Y$ .

$B(Q) = \frac{1}{1- 1+\eta } Q^{1- 1+\eta }$	$\eta = 0.00$	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
(2.00, 0.00)	+	+	+	+	+	+	+	+	+
(2.25, 0.00)	+	+	+	+	+	+	+	+	+
(2.50, 0.00)	+	+	+	+	+	+	+	+	+
$(\beta, \sigma_\beta^2)$ for									
(2.00, 0.33)	-	-	-	-	-	-	-	-	-
$C(q_i; \theta_i) :=$									
(2.25, 0.33)	-	-	-	-	-	-	-	-	-
$[\gamma + \theta_i]q_i + \frac{c}{2}q_i^\beta$									
(2.50, 0.33)	+	-	-	-	-	-	-	-	-
(2.00, 1.33)	-	-	-	-	-	-	-	-	-
(2.25, 1.33)	-	-	-	-	-	-	-	-	-
(2.50, 1.33)	-	-	-	-	-	-	-	-	-

of commitment (Acemoglu, 2003). Instead of relying on political frictions, the current contribution identifies an inefficiency arising due to countries’ boundaries of political power. In doing so, it complements the rich body of knowledge using political frictions to explain the prevalence of inefficient policy instruments.

The results in this paper relate to the literature in international policy cooperation (Rogoff, 1985; van der Ploeg, 1988; Kehoe, 1989). This literature examines how the credibility problem leads cooperative policies to backfire and reduce welfare. International cooperation undermines crucial devices restraining regulators (e.g., central banks and finance ministries) from behaving credibly. Regulatory failure allows central banks to impose a surprise inflation tax (Rogoff, 1985; van der Ploeg, 1988) and finance ministers to expropriate the gains from savings using capital taxes (Kehoe, 1989). The results in this paper complement this literature in several ways. First, it focuses on an inefficiency that arises even in the absence of the credibility problem, as regulators commit to policies before firms choose abatement. Second, as opposed to Kehoe (1989), the inefficiency in focus here arises even when the public good improves welfare. Third, this inefficiency arises despite the regulator being benevolent and takes into account the welfare of all citizens in contrast to Rogoff (1985) and van der Ploeg (1988). Finally, this inefficiency arises from risk externality. This inefficiency cannot emerge in a setting with perfect information (Kehoe, 1989).

Besides, the contributions of this paper complement the literature on distortions of market-based policies with incomplete coverage, such as the carbon leakage literature (Markusen, 1975; Hoel, 1994; Harstad, 2012) and the green paradox literature (Sinn, 2008; van der Ploeg and Withagen, 2012; Jensen et al., 2015). The current contribution highlights an inefficiency arising even when the coverage of a policy is complete. The results in this paper also contribute to the literature focusing on reducing emissions and maintaining the supply of a domestic public good (Pigou, 1920; Weitzman, 1974).<sup>9</sup>

Lastly, the current paper extends Mideksa and Weitzman (2019) to explore the efficiency properties of countries’ choice of policy instruments. While Mideksa and Weitzman (2019) use a framework of multiple countries with independent shocks and establish the main result that the policy instrument a country chooses in equilibrium is governed by Weitzman’s rule, the current paper generalizes the shocks to any degree of correlation and examines the global efficiency properties of the choice of policy instruments. Generalizing the shocks have important implications. For example, in the extreme case of a

<sup>9</sup> Some of its many contributions include the examination of alternative forms of uncertainty (Adar and Griffin, 1976; Roberts and Spence, 1976), various aspects of nonlinearities (Weitzman, 1978; Yohe, 1978; Kelly, 2005), a correlation between uncertain marginal costs and benefits (Yohe, 1978; Stavins, 1996), coalition formation and international agreements (Endres and Finus, 2002; Eichner and Pethig, 2015; Kornek and Marschinski, 2018), multiple pollutants and countries (Ambec and Coria, 2013, 2018; Mideksa and Weitzman, 2019), stock externalities (Hoel and Karp, 2002; Newell and Pizer, 2003; Goulder and Schein, 2013; Karp and Traeger, 2018), intensity inefficiency in a non-cooperative setting (e.g., Nordhaus and Yang, 1996; Nordhaus, 2015) and many more contributions not cited here due to space constraints.

perfectly correlated global cost shock, both the cooperatively more efficient and the equilibrium policy instruments exhibit asymmetry across countries. This result contrasts with the symmetric choice of policy instruments that Mideksa and Weitzman (2019) find under independent shocks. Thus, the current paper discovers a negative externality arising from sovereign nations non-cooperatively choosing their own Pigouvian fees. It also identifies the conditions in which this inefficiency can be significant, and generalizes the results to different settings.

### 7. Conclusion

In his Nobel Lecture, Nordhaus (2019, p. 2006) asks why “why have global policies on climate change been so ineffective compared to many other national policies.” To make progress on this question, the analysis has focused on a framework in which countries choose both the type and intensity of a policy in a strategic setting while facing technological uncertainty. Countries’ choice of policy instruments can favor the price instrument, which in turn can give rise to the PvQ inefficiency. Focusing on efficiency, this paper has examined the conceptual origin and significance of the PvQ inefficiency.

As a substantive contribution, this study responds to Acemoglu (2003, p. 649), who invites “future research on the causes of inefficient policies and the factors preventing the application of the political Coase theorem.” Not only has the analysis isolated and identified the cause of the PvQ inefficiency, but it has also resulted in insights complementary to those in the literature. The PvQ inefficiency is of interest for several reasons. First, it arises despite countries adopting a market-based rather than a command-and-control policy instrument. Second, it persists even in the absence of political frictions, such as a lack of credible commitments, agency problems, or the influence of organized interest groups, which have also been considered the primary political sources of policy distortions in the literature. Third, it arises despite market-based policy instruments having complete geographical coverage and lacking the inter-temporal perverse incentive causing problems of carbon leakage and the green paradox. The PvQ inefficiency arises due to the interaction between an externality spanning multiple countries and due to uncertainty regarding technological possibilities affecting the abatement costs of sovereign countries.

To sum up, economic analysis suggests that pricing pollution is the most efficient way of addressing a pollution problem. The main results advanced in this paper depend crucially on two assumptions. First, that a country’s pollution abatement effort has the characteristic of a public good; and second, that regulators draw policies under incomplete information. Both assumptions are standard (Nordhaus, 2015), pp. 1339–1340) and considered realistic (e.g., Barrett, 2007; Nordhaus, 2015; Stiglitz, 2019). The analysis suggests that a political institution (e.g., national sovereignty) can interact with policy instruments in a non-obvious manner.<sup>10</sup> However, several institutional rules govern and

<sup>10</sup> This observation is not new. Krugman (1991, pp. 2–3) writes: “... the tendency of international economists to turn a blind eye to the fact that countries both occupy and exist in space – a tendency so deeply entrenched that we rarely even realize we are doing it – has, I would submit, had some serious costs. These lie not so much in lack of realism – all economic analysis is more or less unrealistic – as in the exclusion of important issues and, above all, of important sources of evidence.”

shape the international political economy. Thus, there is a need for more conceptual and empirical research on the consequences of the existing political institutions for identifying ways of addressing various environmental problems.

**Declaration of competing interest**

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to <https://doi.org/10.1016/j.pubecp.2022.100014>.

**Appendix. Proofs**

**Proof of Proposition 1.** The expected welfare from adopting the price instrument is

$$\begin{aligned} \mathbb{E}W^i(q_i(\hat{t}_i; \theta_i), q_{-i}(I_{-i}; \theta_{-i})) &\approx B(\hat{Q}) + \frac{1}{2}B''(\hat{Q})\sigma_{\sum_{M \cup \{i\}} q_j(\hat{t}_j; \theta_j)}^2 \\ &- C_i(\mathbb{E}q_i(\hat{t}_i; \theta_i)) - \frac{1}{2}C_i''(\mathbb{E}q_i(\hat{t}_i; \theta_i))\sigma_{q_i(\hat{t}_i; \theta_i)}^2. \end{aligned}$$

Similarly, the expected welfare from adopting the quantity instrument is

$$\begin{aligned} \mathbb{E}W^i(q_i(\hat{\kappa}_i; \theta_i), q_{-i}(I_{-i}; \theta_{-i})) &\approx B(\hat{Q}) + \frac{1}{2}B''(\hat{Q})\sigma_{\sum_M q_j(\hat{t}_j; \theta_j)}^2 \\ &- C_i(\mathbb{E}q_i(\hat{\kappa}_i; \theta_i)). \end{aligned}$$

For any country  $i$ , adopting the price instrument is welfare improving only if

$$B''(\hat{Q})\sigma_{\sum_{M \cup \{i\}} q_j(\hat{t}_j; \theta_j)}^2 - B''(\hat{Q})\sigma_{\sum_M q_j(\hat{t}_j; \theta_j)}^2 \geq C_i''(\mathbb{E}q_i(\hat{t}_i; \theta_i))\sigma_{q_i(\hat{t}_i; \theta_i)}^2;$$

however, adopting the quantity instrument is cooperatively more efficient than adopting the price instrument if

$$nB''(\hat{Q})\sigma_{\sum_{M \cup \{i\}} q_j(\hat{t}_j; \theta_j)}^2 - nB''(\hat{Q})\sigma_{\sum_M q_j(\hat{t}_j; \theta_j)}^2 \leq C_i''(\mathbb{E}q_i(\hat{t}_i; \theta_i))\sigma_{q_i(\hat{t}_i; \theta_i)}^2.$$

Country  $i$  adopts the price instrument when the quantity instrument is more efficient only if

$$\begin{aligned} \frac{\sigma_{\sum_{M \cup \{i\}} q_j(\hat{t}_j; \theta_j)}^2 - \sigma_{\sum_M q_j(\hat{t}_j; \theta_j)}^2}{\sigma_{q_i(\hat{t}_i; \theta_i)}^2} &\leq \frac{C_i''(\mathbb{E}q_i(\hat{t}_i; \theta_i))}{|B''(\hat{Q})|} \\ &\leq \frac{n\sigma_{\sum_{M \cup \{i\}} q_j(\hat{t}_j; \theta_j)}^2 - n\sigma_{\sum_M q_j(\hat{t}_j; \theta_j)}^2}{\sigma_{q_i(\hat{t}_i; \theta_i)}^2}. \end{aligned}$$

**Proof of Lemma 1.** From (5), it follows that the best response abatement levels to the price intensity  $t_i$  is  $q_i(t_i; \theta_i) = \frac{t_i - C' - \theta_i}{C''}$ . Using (3) to arrive at  $\sum_N \mathbb{E}W^i$ , reinserting the best response abatement into  $\sum_N \mathbb{E}W^i$ , and maximizing  $\sum_N \mathbb{E}W^i$  with respect to  $\{t_i\}$ , one arrives at  $t_i^{**} = \frac{nC''B' + n^2C'B''}{n^2B'' + C''}$ . Again, using the best responses in (3) and maximizing the  $\mathbb{E}W^i$ , one arrives at the  $t_i$  that maximizes country  $i$ 's welfare:  $t_i^* = \frac{C''B' - nB''(B' - C')}{nB'' + C''}$ . Solving for the abatement that  $t_i^*$  and  $t_i^{**}$  induce and reinserting the induced abatement back into (3), and solving for  $\sum_N \mathbb{E}W^i(q_i(t_i^{**}, \theta_i), q_{-i}(t_{-i}^{**}, \theta_{-i})) - \sum_N \mathbb{E}W^i(q_i(t_i^*, \theta_i), q_{-i}(t_{-i}^*, \theta_{-i}))$ , one arrives at (7). □

**Proof of Proposition 2.** Using (5), the best response abatement level to the price instrument becomes  $q_i(t_i; \theta_i) = \frac{t_i - C' - \theta_i}{C''}$ . Using (3) to arrive at  $\sum_N \mathbb{E}W^i$ , inserting  $\{q_i(t_i; \theta_i)\}_{i \in M}$  in  $\sum_N \mathbb{E}W^i$  and solving  $\max_{\{t_i\}_{i \in M}, \{\kappa_i\}_{i \in R}} \sum_N \mathbb{E}W^i$ , one arrives at  $t_i^{**} = \frac{nC''B' + n^2C'B''}{n^2B'' + C''}$  and  $\kappa_i^{**} = \frac{nB' - C'}{n^2B'' + C''}$ .  $\sum_M [\mathbb{E}W^i(q_i(\kappa_i^{**}, \theta_i), q_{-i}(\kappa_{-i}^{**}, \theta_{-i})) - \mathbb{E}W^i(q_i(t_i^{**}, \theta_i), q_{-i}(t_{-i}^{**}, \theta_{-i}))]$  gives (9). Note that Remark 2 implies the PvQ inefficiency is also given by the difference between  $\sum_M [\mathbb{E}W^i(q_i(\kappa_i^*, \theta_i), q_{-i}(\kappa_{-i}^*, \theta_{-i}))]$  and  $\sum_M [\mathbb{E}W^i(q_i(t_i^*, \theta_i), q_{-i}(t_{-i}^*, \theta_{-i}))]$ . □

**Proof of Proposition 3.** The welfare from non-cooperatively determined quantities is given by  $\sum_N \mathbb{E}W^i(q_i(\kappa_i^*; \theta_i), q_{-i}(I_{-i}^*; \theta_{-i}))$ , whereas the welfare from the socially optimal price intensities is  $\sum_N \mathbb{E}W^i(q_i(t_i^{**}; \theta_i), q_{-i}(t_{-i}^{**}; \theta_{-i}))$ . Comparing the value  $\sum_{i=1}^n \mathbb{E}W^i(q_i(\kappa_i^*; \theta_i), q_{-i}(I_{-i}^*; \theta_{-i}))$  with the value  $\sum_N \mathbb{E}W^i(q_i(t_i^{**}; \theta_i), q_{-i}(t_{-i}^{**}; \theta_{-i}))$ , under the assumptions of iid shocks or a global shock, one arrives at the expression stated in the Proposition. □

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