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THE POLLUTION HAVEN HYPOTHESIS

Pollution Havens and the Regulation of Multinationals with Asymmetric Information

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Abstract

This paper develops a common agency model to analyze the strategic interaction between governments in regulating polluting multinationals. We show that when a firm has private information about its production technology relating output to pollution that is difficult to monitor, the information rent extraction behavior of non-cooperative governments will work against the "pollution haven" hypothesis in a Nash equilibrium with or without pooling. The "pollution haven" result is more likely to be reversed in a separating equilibrium than in a pooling equilibrium as a firm's output is further away from the most efficient outcome. This result provides an explanation for why many empirical studies do not support the "pollution haven" hypothesis even after controlling for private non-environmental cost differentials.

KEYWORDS: multinational corporations, environmental regulation, common agency

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One version of the "Pollution Haven Hypothesis" (PHH) is that less developed countries care more about economic growth than environmental protection and hence set lower environmental standards than developed countries.[1] Under freer trade, the hypothesis predicts that multinational firms will relocate to less developed countries to take advantage of their lax environmental standards. Over time, these countries will develop a comparative advantage in pollution-intensive industries and become the "havens" for the world's polluting industries.

In this paper, transboundary pollution can occur and decrease the welfare of the home country if a dirty industry is allowed to move to a foreign country with lax environmental controls so as to reduce its tax obligations. Hence, the creation of a "pollution haven" could reduce world welfare from the home country's point of view. However, the movement of the dirty industry to the foreign country could also raise world welfare because the residents of the foreign country are the ones more directly affected by the pollution but care more about jobs than about pollution (Oates and Schwab, 1988). Indeed, this paper finds that cooperation between governments increases welfare even as the dirty industry moves toward the foreign country with more pollution. Moreover, because of the information asymmetries, the concern that the dirty industry can and will over-pollute the foreign country is not justified.

Grossman and Krueger (1993) and Jaffe et al. (1995) demonstrate that there is little empirical evidence for the existence of "pollution havens" due to factor endowment and economies of scale considerations. Thus, freer trade may not harm the environment. To investigate this issue, Antweiler et al. (2001) and Grossman and Krueger (1993) divide trade's impact on pollution into a scale effect (i.e. aggregate demand for the polluting good), a technique effect (i.e. the pollution intensity of the dirty industry), and a composition effect (i.e. the share of the dirty industry in total output). They estimate the magnitude of these three effects and conclude that freer trade can be neutral or even beneficial to the environment.

This paper focuses on the technique effect under imperfect information and turns attention to the role of regulatory agencies (later referred to as governments). A key factor in regulating pollution is asymmetric information that arises when a government observes neither a multinational firm's pollution level nor its production technology to infer pollution from level of production. The paper demonstrates that the technique effect dominates, as in Antweiler et al., but due to informational reasons rather than a lower cost of capital. Although there have been many improvements in measuring pollution emissions directly and accurately with reasonable costs, incomplete information remains an important obstacle in regulating pollution.[2]

[1]Empirical studies on the relationship between pollution and income include Grossman and Krueger (1995), Komen et al. (1997), Selden and Song (1994), and the World Bank (1992).

[2]The World Bank (1992, p. 78) report also states that, "Ideally, regulators would attempt to change the behavior of resource users by means of direct policies — for instance, by taxing or regulating emissions. But these measures involve a heavy administrative burden because they target individual polluters or resource users."

Given that multinational firms have better information about the pollution intensity of their technology than do regulatory agencies, an efficiency-seeking government needs to design a regulatory regime that induces a firm to reveal its technology. Such a scheme will invariably generate informational rents to firms, which governments seek to minimize. In an open economy, what regulatory regime is optimal depends on the regulatory policies of other countries as well because a polluting multinational firm's output and pollution in one country affect both countries' welfare. By developing a common agency model with footloose multinationals as agents of separate governments, this paper demonstrates that the rent extraction behavior between governments can provide another rationale for why "pollution havens" may not exist and hence why freer trade may be good for the environment. The rent extraction incentive also provides an explanation to the following empirical findings.

Eskeland and Harrison (2003) and OECD (1995) find that, even after discounting factors such as transportation costs, factor costs, economies of scale, and country risks, there is still no significant production surge in the developing countries resulting from multinational firms' incentive to flee environmental costs at home. Javorcik and Wei (2004) extend this empirical pursuit by taking into account the domestic regulatory environment such as corruption. They find only weak evidence that supports the PHH. In testing the PHH in terms of revealed comparative advantages, the findings are mixed. Low and Yeats (1992) find that dirty industries account for a growing share of exports in some developing countries. Xu (1999) finds that export performance of "dirty" goods for most countries remained unchanged between the 1960s and 1990s.

Since the major concern of the PHH is the production reallocation from a developed country to a developing country, the following analysis will consider the case where all multinational firms originate in the home (developed) country that cares more about pollution. Also, the home government knows each firm's technology while the foreign government does not. This assumption is consistent with the finding in Caves (1996), the World Bank (1992) report, and UNCTAD (1993) that the developed countries in general have a lower administrative burden in regulating emissions directly than the developing countries. More generally, as discussed in Bond and Gresik (1997 and 2004), the case with only one uninformed government can capture the strategic interaction between governments just as well as the case where both governments are uninformed.

Without knowing a firm's technology, the foreign government either has to let all firms produce the same output (a pooling output scheme) or to internalize the externality of pollution by assigning different output levels to firms with different reported technologies (a separating output scheme). Thus, the home government can use its superior information to influence a firm's reported technology to the foreign government and hence to manipulate foreign regulatory policies so as to extract rents from the foreign government. On the other hand, since only the home government knows the firm's technology, the foreign government cannot do the same to the home government. The analysis in this paper finds two main conclusions.

First, if the foreign government chooses a separating output scheme, the home government has an incentive to encourage the firm to cheat the foreign government by increasing its production at home to compensate for its loss of production abroad due to cheating. This not only shifts information rent via tax collection from the foreign government to the home government, but also reduces the home government's welfare loss from transboundary pollution (if there is any). Foreseeing this, the foreign government reduces every firm's production abroad to induce truth telling. Alternatively, if the foreign government chooses a pooling output scheme, then a firm's output no longer depends on its reported technology and hence the home government can no longer induce cheating by increasing its domestic production. Therefore, the foreign government preempts any rent extraction from the home government. However, by doing this, the foreign government has to give up internalizing the externality of pollution.

Second, since the home (developed) country cares more about pollution, the above information rent extraction behavior between governments works against the PHH in both a pooling and a separating equilibrium. Moreover, the deviation from the cooperative most efficient outcome is bigger, and hence the "pollution haven" result is more likely to be reversed in a separating than in a pooling equilibrium.[3] At equilibrium, most firms face a separating output scheme in the foreign country. The paper also shows that this rent extraction effect is reinforced by profit repatriation and by transboundary pollution.

There are other cases where governments act strategically in regulating polluting multinationals, but under perfect information. In Dockner and Long (1993), Folmer et al. (1993), and Hoel (1997), this strategic consideration is to reduce transboundary pollution. Copeland (1996) analyzes how the home government affected by transboundary pollution can extract rents from foreign pollution quotas. Markusen et al. (1995) focus on the competition between governments in levying environmental taxes on multinational firms that generate local pollution. As in this paper, a government's major trade-off in regulating polluting multinationals is between the disutility of more pollution and the competition for additional tax revenues. For Markusen et al., the tax revenues come from monopoly profits. In this paper, tax revenues come from information rents.

Moreover, this paper focuses on the asymmetric information problem in Spulber (1988) and Dasgupta et al. (1980), and extends their analysis on regulating local firms in a single principal-agent problem to regulating multinational firms in a common agency problem. The analysis demonstrates that there can be over-production in the home country and under-production in the foreign country compared to the most efficient outcome. This asymmetry is not found in the previous studies and is due to the information rent extraction between the asymmetrically informed governments. This study also allows us to examine how firms with different technologies (private information) may respond differently to a policy change.

The literature on common agency models and regulation of multinationals with asymmetric information has been burgeoning since the early 1990s. Bernheim and Whinston

[3] Bond and Gresik (2004) also shows that, for firms with two discrete types, a pooling equilibrium can be more efficient than a separating equilibrium in a tax competition between governments over one final output.

(1985 and 1986), Laffont and Tirole (1991), Martimort (1992), and Stole (1991) were the first to introduce the common agency model with two uninformed principals and one common agent with either private information or unobservable action. In their models, the two principals have the same information set and the agent's type has the same effect on principals. Many studies have extended this homogeneity assumption. For examples, Bond and Gresik (1997 and 2004) study the case where there is one informed and one uninformed government rather than two uninformed governments, while Biglaiser and Mezzetti (1993) and Mezzetti (1997) extend the study of homogeneous principals to vertically and horizontally differentiated principals, respectively. Other extensions include Biglaiser and Mezzetti (2000), Bond and Gresik (1996), Gal-Or (1991), Ivaldi and Martimort (1994), Martimort (1996), and Olsen and Osmundsen (2001 and 2003).

To analyze the environmental regulation of multinationals by asymmetrically informed governments, this paper develops a common agency model that integrates Stole (1991) and Bond and Gresik (1997 and 2004). In the literature on common agency models, most studies focus on intrinsic common agencies only.[4] This paper shows that whether a firm has to produce in both or neither countries (an intrinsic common agency) or has the freedom to produce in only one country (a delegated common agency) affects only the tax payments at home and abroad, but leaves the equilibrium output levels unchanged. Thus, the rent extraction under asymmetric information works against the PHH regardless of the type of equilibrium. This analysis of the relationship between an intrinsic and a delegated common agency in a separating and a pooling equilibrium is applicable to other common agency problems as well.

The remainder of the paper is organized as follows. Section 1 describes the model. Section 2 shows that cooperation leads to the most efficient outcome, where the PHH always holds. Section 3 derives the non-cooperative Nash equilibrium with and without pooling and discusses the reversal of the "pollution haven" result under asymmetric information. Section 4 concludes and draws some empirical implications.

1. The Model

The model includes two countries, home and foreign, and a competitive industry with a continuum of firms. The production of this competitive industry generates a negative externality either by producing polluting by-products or by using polluting inputs. The product of the polluting industry is homogeneous and is sold at world price. All firms are price takers. Furthermore, the total output in each country is only a small proportion of world production so that each country's government cannot influence the world price by changing its domestic policy. Thus, we can single out distortions of asymmetric information in regulating polluting multinationals.

All firms are identical except for their production technologies indexed by θ. A higher θ means more pollution per unit of production. It is assumed that a firm's technology is

[4] Bernheim and Whinston (1986) provide a formal definition of an intrinsic and a delegated common agency.

determined by its technology know-how so that a firm is endowed with a given θ.[5] Also, each firm uses the same technology at home and abroad.[6] There is no strategic interaction between firms.

As discussed in the introduction, all multinational firms originate in the home (developed) country, whose residents have a higher marginal disutility of pollution. The home government also has superior information than the foreign government. In particular, the home government knows the exact value of each firm's technology parameter θ while the foreign government does not, but knows only the distribution of θ for the whole industry. Hence, θ is a random variable for the foreign government. The industry's technology θ ranges from $\underline{\theta}$ to $\overline{\theta}$ with $\underline{\theta} > 0$. Let $F(\theta)$ be the cumulative distribution function, and $f(\theta)$ be the density function of θ. $F(\theta)$ and $f(\theta)$ are continuous and differentiable with bounded derivatives. Since regulation does not change an existing firm's θ, regulation does not change $F(\theta)$ and $f(\theta)$. It is further assumed that $f(\theta) \neq 0$ for all $\theta \in \Theta$ so that the reciprocal of the hazard rate, $\frac{1-F(\theta)}{f(\theta)}$, is defined for all θ. This inverse hazard rate is assumed to be nonincreasing in θ, i.e. $\frac{d}{d\theta}(\frac{1-F(\theta)}{f(\theta)}) \leq 0$ for all θ.

Similar to the quadratic function used in Spulber (1988), a firm's cost of producing y units of total output in the home country is:

$$C(y,\theta) = \frac{1}{2}c_1 \cdot y^2 + (c_2 \cdot \theta + \xi)y + S, \tag{1}$$

where c_1 is the change of marginal cost with respect to a change in output, c_2 is the change of marginal cost with respect to a change in technology, ξ is a constant component of marginal cost, and $S > 0$ is a small sunk cost of setting up a plant.[7] It is assumed that there is a social welfare trade-off between pollution reduction and private cost reduction so that $c_2 < 0$.

[5] This is true, for example, if the pollution reduction technology is tied to human capital (e.g. R&D) or physical assets, which are either too costly to change after a firm sets up its plant or are not equally available to all firms. Alternatively, if pollution reduction is a matter of a firm's continuous effort or if a firm can choose its technology after knowing a country's environmental regulation, then it is more of a moral hazard problem than an adverse selection problem. In general, these two problems need to be analyzed separately. Under some circumstances, as discussed in Grossman and Hart (1983), a moral hazard problem can be transformed to an adverse selection problem discussed in this paper. The information cost of implementing a given effort under moral hazard is then equivalent to that of enforcing truth telling under adverse selection.

[6] Empirical studies suggest that firms usually use the same technology across countries (Bhagwati and Hudec, 1996; Caves, 1996; Ulph, 1998; UNCTAD, 1993). One reason is that it is more efficient for a firm to specialize in one technology than to operate under different technologies. The other reason is that, when a firm sets up a new plant in a developing country, the firm tends to make its production complying to the higher environmental standards in the developed countries just to avoid any sunk costs that may occur in the future as regulators in the developing countries tighten their requirements.

[7] If there are transportation costs, then the constant marginal cost should be ξ plus a per unit transportation cost if part or all of the output in one country is shipped to consumers in another country. For tractability, the following analysis assumes zero transportation cost. However, this assumption should not change the main results in this paper.

Also, it is assumed that production in the home country exhibits decreasing returns to scale so that $c_1 > 0$. If the sunk cost abroad S^* is not significant, then firms (originated in the home countries) have an incentive to open a new plant in the foreign country with the lower environmental standard.[8] However, firms will not stop producing in the home country because, as derived later, the tax scheme in the foreign country is non-linear and is increasing in a firm's total output to keep pollution under control. Finally, for the private marginal cost to be non-negative for all y and θ, $\xi \geq -c_2 \cdot \overline{\theta} > 0$.

Let $y \geq 0$ denote home production and $y^* \geq 0$ denote foreign production. With technology θ, a multinational firm's total cost of producing in both countries is:

$$TC(y, y^*) = C(y, \theta) + C(y^*, \theta) + cyy^*, \tag{2}$$

where $c \geq 0$ represents the additional operation cost of producing at two different locations rather than one, for example, coordination costs between plants to standardize their products.[9] However, $c_1 > c$ so that it pays firms to become multinationals. Equation (2) ensures that home and foreign production are perfect substitutes so that a firm's cost is minimized by choosing the same production in both countries if their environmental regulations were the same. This rules out the economies of scale effect already studied in Antweiler et al. (2001) and Grossman and Krueger (1993).

Usually, governments use only pure strategies to regulate pollution. Suppose the home government assigns each firm a pair of output and transfer, $\{y(\theta),\ t(\theta)\}$, according to a firm's **true** technology θ. Without knowing each firm's θ, the foreign government uses a direct mechanism to assign each firm a pair of output and transfer, $\{y^*(\hat{\theta}),\ t^*(\hat{\theta})\}$, according to a firm's **reported** technology $\hat{\theta}$.[10] If the foreign government chooses a pair of pooling schemes, then y^* and t^* are constants so that $y^{*'} = t^{*'} = 0$.[11]

It is assumed that the governments offer output and transfer schemes to firms and firms only have the choice of stay or exit. A firm receives a zero profit if it chooses exit. Thus, when its individual rationality constraint is satisfied so that it produces in both countries, a firm's objective function is its profit plus any transfers received from the governments, i.e.

$$u(\hat{\theta}, \theta) = \pi(y(\theta), y^*(\hat{\theta}), \theta) + t(\theta) + t^*(\hat{\theta}), \tag{3}$$

[8] A superscript $*$ of a variable is hereafter used to denote its corresponding variable in the foreign country.

[9] The following discussion will focus on the case where $c > 0$ and the special case where $c = 0$ will be discussed in the appendix.

[10] Alternatively, as in Peters (2003), a direct mechanism can also specify transfer t^* as a function of y^* for each given technology. By the "taxation principle" developed by Guesnerie (1981 and 1995) and Rochet (1986) for a single agent problem and later extended to a common agency problem by Martimort and Stole (2002), we can implement $y^*(\hat{\theta})$ and $t^*(\hat{\theta})$ derived in this paper by specifying t^* as a function of y^* at each $\hat{\theta}$. Thus, the two definitions are compatible. Although direct mechanisms may not be the best mechanisms to model a common agency game as shown in Martimort and Stole (2002), this paper uses the direct mechanism approach in order to derive the equilibrium output levels across countries and hence compare non-cooperative output with cooperative output directly and avoid the complication in deriving explicitly the tax schemes to implement this equilibrium outcome, which is non-essential in this analysis.

[11] Hereafter, a prime denotes the first order derivative with respect to θ and any subscript to a variable denotes the partial derivative of the variable with respect to the subscript.

where

$$(4)\ \pi(y, y^*, \theta) = p \cdot (y + y^*) - \frac{1}{2}c_1(y^2 + (y^*)^2) - (c_2 \cdot \theta + \xi)(y + y^*) - cyy^* - S - S^*,$$

and p is the world price, which is assumed to be greater than or equal to the private average total cost of production so that all firms produce in both countries in the absence of regulation. Otherwise, regulation becomes redundant. Under a direct mechanism, all firms with the same θ have the same output and receive the same transfer.

Since consumers always buy at the world price p, following Copeland and Taylor (1995), it is assumed that pollution in each country only affects a representative consumer's utility through damage to health, but not his/her choice among goods. A firm's damages to the home and foreign consumers, respectively, are given by the following equations:

$$(5)\quad B(y(\theta), y^*(\theta), \theta) = \gamma b\theta(y(\theta) + \alpha y^*(\theta)),$$
$$(6)\quad B^*(y(\theta), y^*(\theta), \theta) = \gamma^* b\theta(y^*(\theta) + \alpha y(\theta)),$$

where γ is the home and γ^* is the foreign marginal disutility of pollution. $b\theta > 0$ is the rate of pollution emission per unit of output so that total emission increases not only as output rises but also as a more polluting technology is used. A more polluting firm causes more damage even with the same amount of output. Thus, damage depends on a firm's technology as well as its output. $\alpha \in [0, 1]$ is the rate at which pollution is transferred from one country to another. By assumption, $\gamma > \gamma^* > 0$. Thus, the PHH holds if all firms produce less at home than abroad.

Suppose each government's objective is to maximize social welfare, i.e. a weighted average of consumer surplus, producer surplus, and tax revenue. In order to compare with the most efficient outcome, the following discussion assigns the same weight to the part of profit that remains in the country (i.e. producer surplus), tax revenue, and the negative damage (i.e. consumer surplus as the rest of it stays the same). Shares (claims on after-tax profits) of multinational firms are assumed to be sold only to home and foreign residents.[12] Hence, the objective functions of the home and the foreign governments are

$$(7)\quad W = \int_{\underline{\theta}}^{\overline{\theta}} [\beta(\pi(s) + t(s) + t^*(s)) - t(s) - B(y(s), y^*(s), s)]f(s)ds$$
$$= \int_{\underline{\theta}}^{\overline{\theta}} [\beta\pi(s) - (1-\beta)t(s) + \beta t^*(s) - B(y(s), y^*(s), s)]f(s)ds,$$

and

$$(8)\quad W^* = \int_{\underline{\theta}}^{\overline{\theta}} [(1-\beta)(\pi(s) + t(s) + t^*(s)) - t^*(s) - B^*(y(s), y^*(s), s)]f(s)ds$$

[12] This assumption can be relaxed if the home government has full information. The profit accrued to a third country works as if a third party levied a profit tax before home and foreign residents split the profit. However, if both governments do not know a firm's technology, then this profit tax to the third country causes the home and foreign governments to deviate from the most efficient outcome even under cooperation as discussed in the next section (see footnote 15).

$$= \int_{\underline{\theta}}^{\overline{\theta}} [(1-\beta)\pi(s) - \beta t^*(s) + (1-\beta)t(s) - B^*(y(s), y^*(s), s)] f(s) ds,$$

where $\beta \in (0, 1)$ is the percentage of shares purchased by home residents and hence is the share of a firm's retained profit contributing to the home government's welfare.[13]

The timing of the model is as follows. First, each firm is endowed with technology θ. Second, the home and foreign governments announce their joint output and transfer schemes if they cooperate. Otherwise, in an intrinsic common agency problem, the home and foreign governments announce their individual output and transfer schemes as functions of a firm's true and reported technology, respectively.[14] In a delegated common agency problem, each government, in addition, announces another set of output and transfer schemes if a firm chooses not to produce in the other country. After knowing the output and transfer schemes, firms decide whether to produce in a country and what technology to report to the foreign government. Finally, production and transfers occur.

2. Cooperative Governments

If the home and foreign governments set their environmental regulations cooperatively, they not only share information, but also choose production jointly. From equations (7) and (8), the home and foreign governments choose output y and y^* for each firm with technology θ to maximize their joint welfare, i.e.

$$\max_{y(\theta), y^*(\theta)} \quad W + W^* = \pi(y, y^*, \theta) - B(y, y^*, \theta) - B^*(y, y^*, \theta). \tag{9}$$

By the small country assumption, price is determined in the international market. The first order conditions are:

$$p = c_1 y + c_2\theta + \xi + cy^* + b\theta(\gamma + \alpha\gamma^*), \tag{10}$$

$$p = c_1 y^* + c_2\theta + \xi + cy + b\theta(\gamma^* + \alpha\gamma). \tag{11}$$

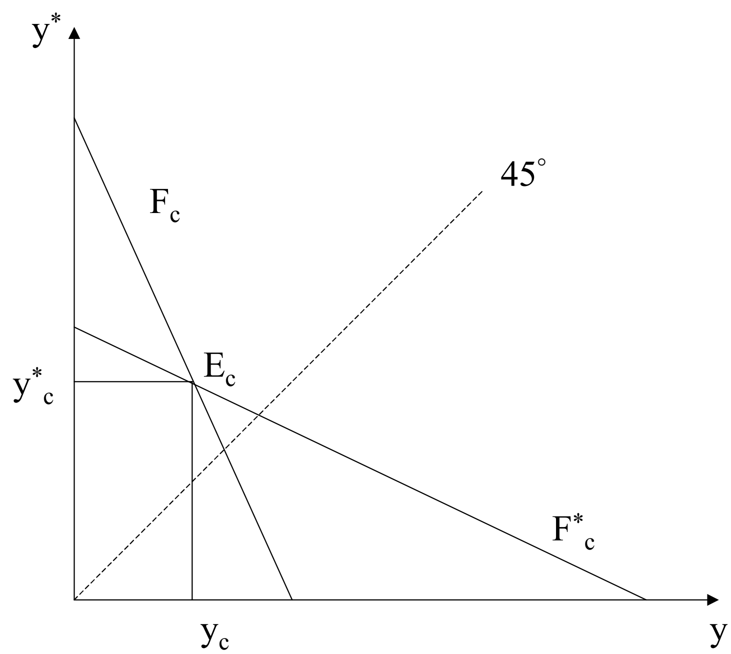
[13] Since this paper examines the competition between governments in extracting firms' profits, each government's welfare depends on the other's tax scheme as well as its own. This externality invalidates the revelation principal so that there may be other kind of equilibria as illustrated in Peters (2003) and also Martimort and Stole (2002), Epstein and Peters (1999) and Peters (2001). However, the rent extraction incentive studied in this paper should still play an important role in the other equilibria. Moreover, according to Theorem 2 in Peters (2003), the pure strategy equilibrium in direct mechanisms derived later in the paper is robust (stays an equilibrium) against the possibility that principals might offer far more complicated communication schemes. Hence, the analysis in this paper is still relevant as it captures the properties of at least one kind of equilibrium no matter what kind of communication mechanisms are feasible.

[14] Since the home government's schemes will not reveal to the foreign government any additional information about a firm's technology and the home government knows all the information, which government announces its schemes first does not change the information structure and hence is not crucial as long as the foreign government announces its schemes before each firm reports its technology. In any case, the home government always takes into consideration the effect of its schemes on the foreign government's schemes and chooses the best as to be discussed in section 3. On the other hand, the foreign government always tries to maximize its utility expecting any collusion between its informed opponents. As both the home government and firms have full information, and will make right expectations of the foreign government's schemes in equilibrium, the home government's optimal choice is renegotiation proof.

The second order condition is satisfied as $c_1 > c$ by assumption. From the first order conditions (10) and (11), the equilibrium output in each country achieves the most efficient outcome, where price p equals the private marginal cost of local production in that country plus its induced marginal damage of pollution to both home and foreign residents (the last term on the right hand side of each condition).[15]

For a given technology θ, solving y as a function of y^* from condition (10) gives the home government's output level that maximizes joint welfare for a given foreign output. To serve as a benchmark to compare with the non-cooperative case, this optimal choice of y at a given y^* is represented by the home government's cooperative first order condition, F_c, as shown in Figure 1. Similarly, solving y^* as a function of y from (11) gives the foreign output level that maximizes joint welfare at a given home output. This optimal choice of y^* at a given y is represented by the foreign government's first order condition, F_c^*. Since $c_1 > c$, F_c is steeper than F_c^*. Hence, the intersection of F_c and F_c^* defines a stable cooperative equilibrium, E_c.

Figure 1: Cooperative Equilibrium (for firms with a given θ)



[15]This result hold even if neither government observes a firm's technology as long as all profits are distributed among home and foreign residents. Without profit outflow, it is easy to see from equation (9) that the joint welfare is independent of transfers. Thus, the governments can internalize the information cost and implement the most efficient outcome by letting each multinational firm be the residual claimant of all consumer surpluses and hence eliminating any incentive to cheat. This fails if part of a firm's profit goes to residents in a third country.

Subtracting condition (10) from (11) gives

$$(c_1 - c)(y - y^*) = b\theta(1 - \alpha)(\gamma^* - \gamma). \quad (12)$$

Since $\gamma > \gamma^*$, $0 \le \alpha \le 1$ and $c_1 > c$, $y \le y^*$ for all θ. All firms produce less in the country with a higher marginal disutility of pollution, i.e. E_c lies above the 45° line, unless pollution is perfectly mobile ($\alpha = 1$) so that $y = y^*$. Moreover, although transboundary pollution reduces the production gap between countries compared with the case without transboundary pollution ($\alpha = 0$), transboundary pollution by itself cannot reverse the "pollution haven" result.

Proposition 1. *Cooperative governments implement the most efficient outcome that internalizes national as well as international externalities via information sharing. The PHH holds under cooperative governments regardless of transboundary pollution: all firms produce more in a country with a lower marginal disutility of pollution than in a country with a higher marginal disutility.*

3. Non-Cooperative Governments

In the non-cooperative case, governments no longer maximize joint welfare. Instead, each maximizes individual welfare. As a result, each cares how profits are distributed between them, which depends on both a country's profit share β and its tax revenue relative to the other government's. With asymmetric information, the home government has no incentive to reveal a firm's true θ to the foreign government. The foreign government has to design a pair of output and transfer schemes, $\{y^*(\hat{\theta}), t^*(\hat{\theta})\}$, based on a firm's reported technology $\hat{\theta}$. Thus, the crucial points of competition between governments in this common agency problem are the home government's attempt to extract information rent from the foreign government and the foreign government's effort to counteract such an attempt.

In a separating equilibrium, the fully informed home government has an incentive to encourage firms to cheat the foreign government so as to make the foreign government pay a higher information rent to firms, which eventually becomes the home government's tax revenue. As home and foreign production are substitutes in a firm's profit function and total production exhibits decreasing returns to scale, the home government wants to increase domestic production above a firm's most efficient level so that each firm has a bigger incentive to report a false θ to cut both its tax and production abroad. This forces the foreign government to pay a higher information rent in order to induce truth telling. Because this (first order) revenue gain outweighs the additional (second order) damage from more pollution, home welfare rises at the expense of foreign welfare. Meanwhile, to counteract the home government's rent extraction attempt, the foreign government further reduces each firm's production in the foreign country to discourage cheating.

By increasing its local output to extract information rents, the home government reduces production in the foreign country. Hence, if pollution is transboundary, asymmetric information provides the home government an opportunity to use its superior information not only to internalize the externality of home production, but also to reduce transboundary pollution from abroad.[16] Thus, the "pollution haven" result is more likely to be reversed if pollution crosses national boundaries.

To demonstrate the above arguments, we solve the common agency problem. A firm's net profit as a function of its true type (θ) and its reported type ($\hat{\theta}$) is

$$U(\hat{\theta}, \theta) \triangleq u(y(\theta), y^*(\hat{\theta}), t(\theta), t^*(\hat{\theta}), \theta). \tag{13}$$

In equilibrium, the foreign government's output and tax schemes, $y^*(\hat{\theta})$ and $t^*(\hat{\theta})$, must be implementable and feasible so that $U(\hat{\theta}, \theta)$ is maximized at $\hat{\theta} = \theta$. Thus, the local first order necessary condition for implementability is

$$t^{*'}(\theta) = -\pi_{y^*}(y(\theta), y^*(\theta), \theta) y^{*'}(\theta). \tag{14}$$

Applying Theorem 12 in Chapter 2 of Hurewicz (1958), there exists a transfer scheme $t^*(\theta)$, which satisfies the above condition at all points where y and y^* are differentiable.[17] From (A.3) in the appendix, the local second order necessary condition for implementability is

$$(c_2 + c y^{'}) y^{*'} \leq 0. \tag{15}$$

In an intrinsic common agency problem, the home government (with full information) extracts all retained profits from firms and leaves them with zero utility.[18] At a given pair of output and tax schemes $(y^*(\hat{\theta}), t^*(\hat{\theta}))$ set by the foreign government satisfying condition (14), the home government's maximization problem is:

$$\max_{y(\theta), t(\theta)} \quad \beta\pi(y(\theta), y^*(\hat{\theta}), \theta) - (1-\beta)t(\theta) + \beta t^*(\hat{\theta}) - B(y(\theta), y^*(\hat{\theta}), \theta) \tag{16}$$

$$s.t. \quad \pi(y(\theta), y^*(\hat{\theta}), \theta) + t(\theta) + t^*(\hat{\theta}) = 0, \tag{17}$$

where $\hat{\theta}$ is a function of y. Hence, when choosing y, the home government also considers how y affects $\hat{\theta}$ and thus y^* as discussed later in deriving the first order conditions. Substituting $t(\theta) = -(\pi(y(\theta), y^*(\hat{\theta}), \theta) + t^*(\hat{\theta}))$ from the constraint into the objective function gives the home government's simplified maximization problem:

$$\max_{y(\theta)} \quad \Lambda = \pi(y(\theta), y^*(\hat{\theta}), \theta) + t^*(\hat{\theta}) - B(y(\theta), y^*(\hat{\theta}), \theta). \tag{18}$$

[16] In this case, although the world price stays the same, firms still have an incentive to reallocate their production across countries to take advantage of the differences in the tax schemes. Hence, as the governments change their environmental policies, they can affect the output and hence transboundary pollution across countries. This incentive is more apparent with the alternative direct mechanism specification discussed in footnote 10.

[17] In a pooling equilibrium, $y^{*'} = t^{*'} = 0$ so that (14) still holds. Firms will report their true θ to the foreign government as they cannot gain from cheating. Meanwhile, the foreign government chooses not to use this information to charge a more polluting firm a higher tax.

[18] The intuition of this policy is similar to that of capital export neutrality. Since the home government has full information so that taxation does not alter domestic production, extracting all retained profits minimizes the gain to foreign shareholders.

In a delegated common agency problem, a firm can choose to produce only in the foreign country. The above analysis stays the same except that $t(\theta) = -(\pi(y(\theta), y^*(\hat{\theta}), \theta) + t^*(\hat{\theta})) + \pi(0, y_0^*(\theta), \theta) + t_0^*(\theta)$, where $y_0^*(\theta)$ and $t_0^*(\theta)$ are the foreign government's output and tax schemes when $y = 0$.[19] Since $y_0^*(\theta)$ and $t_0^*(\theta)$ are independent of $y(\theta)$ at equilibrium, this will only change the home government's transfer scheme, but not output as the first order condition of the maximization problem (18) stays the same. Footnote 20 shows a similar property for the foreign government's maximization problem. Hence, whether a firm has to produce in both or neither countries (an intrinsic common agency) or can choose to produce in only one country or both (a delegated common agency) will only affect the home and foreign transfer schemes, but will have no effect on the output levels at home and abroad.

The foreign government's maximization problem is

$$(19) \quad \max_{y^*(\theta), t^*(\theta)} \int_{\underline{\theta}}^{\overline{\theta}} ((1-\beta)\pi - \beta t^* + (1-\beta)t - B^*) f(\theta) d\theta$$

$$(20) \quad s.t. \quad (IC)\ u(y(\theta), y^*(\theta), t(\theta), t^*(\theta), \theta) \geq u(y(\theta), y^*(\hat{\theta}), t(\theta), t^*(\hat{\theta}), \theta)$$

$$(21) \quad (IR)\ u(y(\theta), y^*(\theta), t(\theta), t^*(\theta), \theta) \geq 0.$$

Following Mirrlees (1971), let $U(\theta)$ be a firm's indirect utility function. Thus, (IC) implies that $U(\theta) = \max_{\hat{\theta}} u(\hat{\theta}, \theta) = \pi(y(\theta), y^*(\hat{\theta}), \theta) + t(\theta) + t^*(\hat{\theta})$, which yields equation (14). From the envelope theorem, $\frac{dU}{d\theta} = u_\theta = \pi_\theta + \pi_y y' + t'$ so that $U(\theta) = \int_{\underline{\theta}}^{\theta} u_\theta(y(s), y^*(s), s) ds + u(\underline{\theta})$. Since it is never profitable for the foreign government to give any information rent to the lowest type (the highest cost) firm, $u(\underline{\theta}) = 0$.[20] We can then write

$$(22) \quad U(\theta) = \int_{\underline{\theta}}^{\theta} [\pi_\theta(y(s), y^*(s), s) + \pi_y(y(s), y^*(s), s) y'(s) + t'(s)] ds.$$

Since $t^* = U - \pi - t$, the foreign government's objective function becomes

$$(23) \quad (1-\beta)\pi - \beta(U - \pi - t) + (1-\beta)t - B^* = \pi + t - B^* - \beta \int_{\underline{\theta}}^{\theta} [\pi_\theta + \pi_y y' + t'] ds.$$

[19] If $y = 0$, the problem degenerates to a single principal-agent problem with adverse selection. Following Mirrlees (1971) and Fudenberg and Tirole (1991), it is easy to prove that $y_0^*(\theta)$ satisfying $p = c_1 y^* + c_2\theta + \xi + \gamma^* b\theta - \beta \frac{1-F(\theta)}{f(\theta)} c_2$ and $t_0^*(\theta)$ satisfying (14) with $t_0^*(\underline{\theta}) = -\pi(0, y_0^*(\underline{\theta}), \underline{\theta})$ are the solution to the single principal-agent problem. Clearly, the monotonicity condition, $y^{*'} > 0$, is satisfied.

[20] This holds in both an intrinsic and a delegated common agency problem. For an intrinsic common agency, the home and foreign tax schemes for a firm with $\underline{\theta}$ are jointly determined by the condition, $t(\underline{\theta}) + t^*(\underline{\theta}) = -\pi(y(\underline{\theta}), y^*(\underline{\theta}), \underline{\theta})$ so that $u(\underline{\theta}) = 0$. For a delegated common agency, $u(\underline{\theta}) = \pi(0, y_0^*(\underline{\theta}), \underline{\theta}) + t_0^*(\underline{\theta}) + \pi(y_0(\underline{\theta}), 0, \underline{\theta}) + t_0(\underline{\theta})$, where $y_0(\underline{\theta}) = \frac{p-(c_2\underline{\theta}+\xi+\gamma b\underline{\theta})}{c_1}$ and $t_0(\underline{\theta}) = -\pi(y_0(\underline{\theta}), 0, \underline{\theta})$ if $\beta < 1$. If $\beta > 0$, then at $y = 0$, $t_0^*(\underline{\theta}) = -\pi(0, y_0^*(\underline{\theta}), \underline{\theta})$. Hence, for $0 < \beta < 1$, $u(\underline{\theta}) = 0$. In fact, from equations (14) and (17), $U_\theta = 0$ so that all firms get zero utility at equilibrium as the fully informed home government taxes away all firms' residual surpluses.

Integration by parts gives

$$\int_{\underline{\theta}}^{\overline{\theta}} \int_{\underline{\theta}}^{\theta} [\pi_\theta(y(s), y^*(s), s) + \pi_y(y(s), y^*(s), s)y'(s) + t'(s)] f(\theta) ds d\theta$$

$$= \int_{\underline{\theta}}^{\overline{\theta}} \frac{1 - F(\theta)}{f(\theta)} [\pi_\theta(y(\theta), y^*(\theta), \theta) + \pi_y(y(\theta), y^*(\theta), \theta)y'(\theta) + t'(\theta)] f(\theta) d\theta.$$

Under the monotonicity condition, $y^{*'} \geq 0$, proved in the appendix, the foreign government's maximization problem at a given pair of home output and tax schemes, $(y(\theta), t(\theta))$, reduces to the following:

$$\text{(24)} \quad \max_{y^*(\theta)} \Lambda^* = \int_{\underline{\theta}}^{\overline{\theta}} [\pi(y, y^*, \theta) - \beta \frac{1 - F}{f} (\pi_\theta(y, y^*, \theta) + \pi_y(y, y^*, \theta)y')] f(\theta) d\theta + \int_{\underline{\theta}}^{\overline{\theta}} \left(t - \beta \frac{1 - F}{f} t' - B^*(y, y^*) \right) f(\theta) d\theta.$$

It is easy to see that the transfer schemes are differentiable and the appendix proves that Λ and Λ^* are strictly concave in y and y^*, respectively, and that both have an interior maximum. Given the foreign government's tax scheme derived from (14), the first order conditions of (18) and (24) by piecewise differentiation are

$$\text{(25)} \quad p = c_1 y + c_2 \theta + \xi + \gamma b \theta + c y^* + \alpha \gamma b \theta y^{*'} \frac{d\hat{\theta}}{dy},$$

$$\text{(26)} \quad p = c_1 y^* + c_2 \theta + \xi + \gamma^* b \theta + c y - \beta \frac{1 - F(\theta)}{f(\theta)} (c_2 + c y'),$$

where $y^{*'} \frac{d\hat{\theta}}{dy}$ is 0 if $y^{*'} = 0$ and is $\frac{c y^{*'}}{c_2 + c y'}$ if $y^{*'} \neq 0$.[21] This term, calculated in the appendix, reflects a strategic interaction between governments. It gives how much the home government can affect the foreign government's output by changing a firm's production at home to encourage the firm to report a false θ to the foreign government. As to be explained in the following subsections, this strategic effort of the home government becomes fruitless ($y^{*'} \frac{d\hat{\theta}}{dy} = 0$) if the foreign government chooses a pooling output scheme ($y^{*'} = 0$) or if there is no transboundary pollution ($\alpha = 0$).[22]

[21] There is no loss of generality here in restricting analysis to piecewise differentiation as the home government has full information and all the terms in the foreign government's objective function have second order derivatives.

[22] Obviously, the last term also becomes zero if the production at home and abroad are unrelated in a firm's profit function ($c = 0$). This case is discussed in the appendix. Clearly, if $\alpha = \beta = c = 0$, then the non-cooperative outcome collapses to the most efficient cooperative outcome. In this extreme case, there is no incentive for the home government not to convey its information to the foreign government.

Since all functions are continuous and have bounded derivatives to the third order, the Lipschitz condition is satisfied uniformly. From Theorem 11 and 12 in Chapter 2 of Hurewicz (1958), there exists a unique solution satisfying the above conditions from any initial point (y_0, y_0^*, θ). Thus, although different initial conditions lead to different equilibrium output schemes, (25) and (26) characterize the common property of all output schemes that maximize the non-cooperative individual welfare of home and foreign governments.[23]

These schemes are locally and globally implementable if and only if the monotonicity condition ($y^{*'} \geq 0$) and the local second order necessary condition for implementation ($(c_2 + cy^{'})y^{*'} \leq 0$) are satisfied. The appendix proves that the monotonicity condition holds if $-c_2 \geq \gamma b$, which ensures that the production cost advantage of a more polluting firm is big enough for both home and foreign governments to let this firm produce more than a cleaner firm.[24]

3.1 Separating Equilibrium

From the monotonicity and local implementability conditions, the appendix proves that the home and foreign outputs are strategic substitutes. If the foreign government chooses a separating output scheme so that $y^{*'} \neq 0$, then $y^{*'} \frac{d\hat{\theta}}{dy} \leq 0$ and $c_2 + cy^{'} < 0$. Since the last term in condition (25) is negative unless $y^{*'} = 0$ or $\alpha = 0$ or $c = 0$, as discussed at the beginning of this section, the home government's rent extraction incentive raises the home non-cooperative output above the output that maximizes joint welfare at any given foreign output. Hence, the home government's non-cooperative first order condition, F_{nc}, shifts to the right of F_c as shown in Figure 2.

If there is no transboundary pollution ($\alpha = 0$), then the last term in (25) becomes zero so that F_{nc} stays at F_c. This is because the informed home government collects a firm's

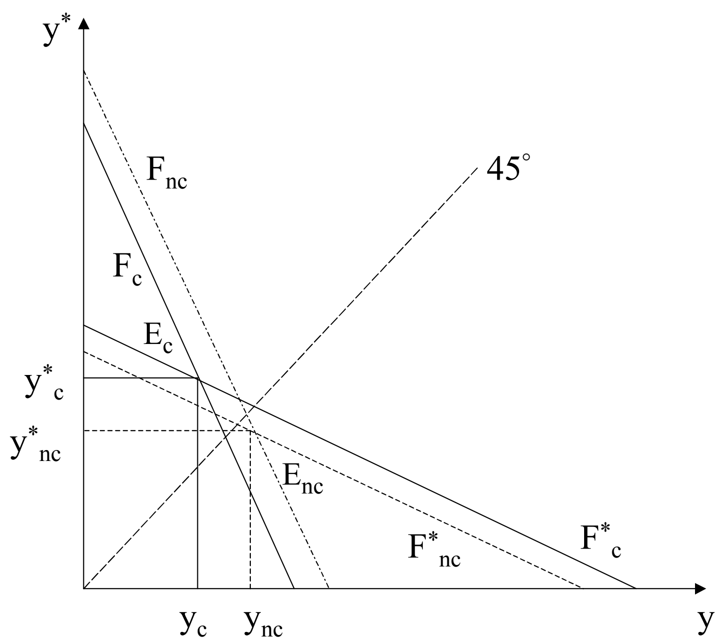
[23] A common agency problem with asymmetrically informed principals usually results in multiple equilibria. This is because the uninformed principal's incentive compatible constraint depends on the informed principal's schemes (as in this case, U_θ depends on $y(\theta)$ and $t(\theta)$), which in turn, depend on how the uninformed principal responds. Bond and Gresik (2004) illustrate this possibility of multiple equilibria as the informed principal chooses different transfer schemes. This multiplicity usually disappears as we move to a common agency with symmetrically uninformed principals. As studied in Martimort and Stole (2003), less information imposes more restrictions on the set of reasonable conjectures and hence can lead to a unique robust equilibrium. In this paper, since the relation of output levels between countries is derived from the first order necessary conditions, which must hold in all equilibria, multiplicity does not matter too much in deriving the effect of asymmetric information on the "pollution haven" hypothesis.

[24] Otherwise, the optimal output should be decreasing in θ. Any output scheme decreasing in θ will not be implementable when the marginal cost of production decreases in θ, i.e. $c_2 < 0$. This is because $y^{*'} \geq 0$ is necessary and sufficient for implementability under the single crossing condition $\pi_{y\theta} = -c_2 > 0$ (Chapter 7, Fudenberg and Tirole, 1991). However, if $c_2 > 0$, then there will be a second-best implementable output scheme which is decreasing in θ. In this case, a cleaner firm with a lower θ also has a lower marginal cost. There will be no social trade-off between cost reduction and pollution reduction. Hence, this case is less interesting.

residual profit in equilibrium. Without transboundary pollution, the home government's preferences over output and tax abroad coincide with a firm's private preferences.

The foreign government's incentive compatibility constraint ensures that the last term in condition (26), $-\beta\frac{1-F(\theta)}{f(\theta)}(c_2 + cy')$, is positive for all firms with $\theta < \bar{\theta}$. This demonstrates that, at each given home output, the foreign government chooses a lower output than the output that maximizes joint welfare to induce truth telling. cy' in the last term reflects the impact of the home government's rent extraction attempt on the foreign government's equilibrium output scheme as discussed at the beginning of this section. Asymmetric information shifts the foreign government's non-cooperative first order condition, F^*_{nc}, to the left of F^*_c. Transboundary pollution has no effect on F^*_{nc} as the foreign government does not have the information advantage to affect the home government's output decision.

Figure 2: Non-Cooperative Equilibrium (for firms with a given $\theta < \bar{\theta}$)



In sum, asymmetric information in a common agency model has two effects. One is to **decrease** the output in a country with inferior information further below its output in a single principal-agent problem with asymmetric information. The other is to **increase** the output in a country with superior information. This latter rent extraction effect is absent in a single principal-agent problem. In this paper, both of these two effects weaken the "pollution haven" effect and can even reverse it as shown in Figure 2 for firms with $\theta < \bar{\theta}$.[25]

[25] For firms with $\theta = \bar{\theta}$, both governments choose their cooperative best responses if $\alpha = 0$. This is consistent with the standard result that there is no distortion "at the top", i.e. for those firms with the most

Moving from cooperation to non-cooperation, the governments not only stop sharing information as discussed above, but also exclude the pollution damage imposed on consumers in another country from their individual welfare functions. Compared with the cooperative case, transboundary pollution further shifts F_c out by $\gamma^* \alpha b\theta$ and F_c^* up by $\gamma \alpha b\theta$. This reinforces the previous effect on the home government's first order condition, but makes the overall effect on the foreign government's first order condition ambiguous, depending on the relative size of $-\beta \frac{1-F(\theta)}{f(\theta)}(c_2 + cy^{'})$ and $\gamma \alpha b\theta$.

We can address this ambiguity mathematically and analyze the effects of asymmetric information more rigorously by subtracting (25) from (26). If $y^{*'} \neq 0$,

$$(27) \qquad (c_1 - c)(y - y^*) = b\theta(\gamma^* - \gamma) - \beta \frac{1-F}{f}(c_2 + cy^{'}) - \frac{\alpha\gamma b\theta c y^{*'}}{c_2 + cy^{'}}.$$

From condition (27), a country's relative output depends on the country's relative marginal disutility of pollution (the first term on the right hand side), the rent extraction effect (the second term), and the transboundary pollution effect resulting from the home government's attempt to use its superior information to reduce transboundary pollution (the third term) by adjusting its transfer scheme. Obviously, the third term becomes zero if pollution has local effects only.

Since $c_2 + cy^{'} < 0$, the rent extraction effect works against the PHH as long as some profits accrue to home residents, i.e. $\beta > 0$, so that the foreign government does lose part of its information rent payments to firms. This rent extraction effect increases with the profit share accruing to home residents as the second term is increasing in β. The transboundary pollution effect reinforces the rent extraction effect as $y^{*'} > 0$ and $\frac{\alpha\gamma b\theta c y^{*'}}{c_2+cy^{'}} < 0$ in a separating equilibrium. This is consistent with the empirical result in Bui (1998) that the gain from cooperation is large when there is severe transboundary pollution. Compared with the cooperative outcome, asymmetric information under non-cooperation always decreases foreign output and increases home output. This distorts the "pollution haven" result and can completely reverse it if $-\beta \frac{1-F}{f}(c_2 + cy^{'}) - \frac{\alpha\gamma b\theta c y^{*'}}{c_2+cy^{'}} > b\theta(\gamma - \gamma^*)$.[26]

3.2 Pooling Equilibrium

If the foreign government chooses a pooling output scheme, then the last term in (25) and that in (27) become zero. F_{nc} stays at F_c for all firms and the foreign government pays no information rent. The "pollution haven" result is reversed only if $-\beta \frac{1-F}{f}(c_2 + cy^{'}) >$

polluting technology.

[26]If the home and foreign governments are both uninformed of a firm's production technology, then the rent extraction incentive will shift each government's non-cooperative first order condition to the right while the usual incentive compatibility constraint will shift each government's non-cooperative first order condition to the left. Thus, the overall effect of asymmetric information on a country's output and hence the "pollution haven" hypothesis in a common agency problem depends on the relative effectiveness of the rent extraction behavior between governments as analyzed in Wu (2000).

$b\theta(\gamma - \gamma^*)$. As studied in Bond and Gresik (1997 and 2004) and Mezzetti (1997), the appendix shows that such a Nash equilibrium with pooling can exist. Also, as in Bond and Gresik (2004), a non-cooperative Nash equilibrium with pooling is closer to the co-operative equilibrium and hence the most efficient outcome than a separating equilibrium because $-\frac{\alpha\gamma b\theta c y^{*'}}{c_2+cy'} > 0$.

However, in a pooling equilibrium, the foreign government has to give up using information on a firm's production technology to internalize the externalities of pollution. The appendix proves that it is only optimal for the foreign government to choose a pooling equilibrium over some narrow intervals of θ and only if $\gamma/\gamma^* < c_1/c$. If the interval is wide, then the externality of pollution will be too high for the foreign government to choose pooling. If the marginal disutility in the home country is much bigger than that in the foreign country (i.e. γ/γ^* is large), but the degree of decreasing returns to scale is not much bigger than the degree of diseconomies of scope (i.e. c_1/c is small), then it is much more profitable for firms to concentrate their production in the foreign country regardless of the home output level so that the home government has limited influence over a firm's production abroad and hence its ability to extract information rent is limited. The benefit of a separating over a pooling equilibrium is bigger than the cost. Thus, the foreign government chooses a separating output scheme for all firms with $\theta < \bar{\theta}$ if $\gamma/\gamma^* > c_1/c$.

Proposition 2. *The rent extraction effect between non-cooperative governments with asymmetric information can by itself reverse the "pollution haven" result: polluting firms can produce more in a developed country than in a developing country. This rent extraction effect is reinforced by profit repatriation and transboundary pollution. These results hold for firms both as intrinsic common agents and as delegated common agents. The results also do not depend on whether pooling exists for some firms or not. Although the outcome with pooling is closer to the most efficient outcome than without, pooling is possible only if $\gamma/\gamma^* < c_1/c$ and can only exist for firms with very similar technologies.*

4. Conclusions and Extensions

This paper develops a common agency model to analyze the strategic interaction between two governments in regulating polluting multinationals. When the foreign government (in a developing country) cannot observe a multinational firm's level of pollution and the cleanliness of its production technology, the strategic rent extraction behavior between governments weakens the "pollution haven" effect. The output levels in a country not only depend on that country's marginal disutility of pollution (γ/γ^*), but also depend on its profit share (β), the degree of transboundary pollution (α), and most importantly, the increase in marginal cost for a firm with a more polluting technology (c_2). The rent extraction effect is stronger if a larger share of multinational firms' profits accrues to home residents or if pollution is transboundary. Thus, "pollution havens" may not exist and freer trade may be good for the environment.

The above results apply regardless of whether the foreign government chooses a pooling or a separating output and tax schemes and whether firms have to choose to produce in both or neither countries (intrinsic agents) or they have the freedom to produce in just one country (delegated agents). These results can also be extended to cases where both governments are uniformed about a firm's technology and where governments assign different weights on consumer's and producer's surpluses and tax revenues. The restrictions on the cost function can also be relaxed.[27] The analysis of an intrinsic and a delegated common agency in a separating and a pooling equilibrium in this paper can also be applied to other common agency models on the regulation of multinational firms or the coordination problem between state governments. For example, we can extend the study on the relationship between trade policies and environmental cooperation between governments from the case with local firms to one with multinational firms.

The results in the paper also have some empirical implications. First, for a particular country, we will observe a negative relationship between pollution and that country's marginal disutility of pollution (or income as its instrumental variable) even with asymmetric information. However, for two or more countries, with asymmetric information, we may fail to observe that production is lower in a developed country with a higher marginal disutility of pollution or that revealed comparative advantage concentrates in relatively more polluting industries in the developing countries. Moreover, as firms use technologies with different pollution intensities, the PHH can hold for some most polluting firms, but fail for some relatively cleaner ones. Javorcik and Wei (2004) also emphasize the value of using a firm-level data set in searching for empirical support for the PHH. Finally, the PHH is more likely to hold for industries with relatively standard technology so that there exists a Nash equilibrium with pooling.

Appendix

1. Strategic revelation effects

Rewrite equation (13) gives:

$$\text{(A.1)}\; U(\hat{\theta},\theta) \triangleq p(y(\theta)+y^*(\hat{\theta})) - \frac{1}{2}c_1(y(\theta)^2+y^*(\hat{\theta})^2) - (c_2\theta+\xi)(y(\theta)+y^*(\hat{\theta})) - cy(\theta)y^*(\hat{\theta}) + t(\theta) + t^*(\hat{\theta}) - S - S^*.$$

The first order condition is:

$$\text{(A.2)}\; U_{\hat{\theta}} = py^{*'}(\hat{\theta}) - c_1y^*(\hat{\theta})y^{*'}(\hat{\theta}) - (c_2\theta+\xi)y^{*'}(\hat{\theta}) - cy(\theta)y^{*'}(\hat{\theta}) + t^{*'}(\hat{\theta}) = 0.$$

[27] Although these extensions will make no inherent differences on the strategic interaction between governments, the overall effect can be ambiguous (Wu, 2000). As explained in footnote 26, the home government's non-cooperative output scheme with asymmetric information can be either above or below its output scheme with perfect information if the home government also does not observe each firm's θ. A more general cost function can bring in additional effects, such as economies of scale, which will complicate a firm's production decision.

Totally differentiating the above condition at $\hat{\theta} = \theta$ gives $U_{\hat{\theta}\theta} + U_{\hat{\theta}\hat{\theta}} = 0$. Hence,

(A.3) $$U_{\hat{\theta}\hat{\theta}} = -U_{\hat{\theta}\theta} = (c_2 + cy^{'})y^{*'}.$$

If the local second order necessary condition for implementation, i.e. $(c_2 + cy^{'})y^{*'} \leq 0$, is satisfied, then $U_{\hat{\theta}\hat{\theta}} < 0$. Hence, $U(\hat{\theta}, \theta)$ is strictly concave in $\hat{\theta}$ so that there is a unique $\hat{\theta}$ that maximizes $U(\hat{\theta}, \theta)$.

Following the derivations in Stole (1991) and Mezzetti (1997), to evaluate the strategic revelation (interaction) effect in a pure-strategy differentiable Nash equilibrium, represented by $\frac{\partial\hat{\theta}^*}{\partial y}$ and $\frac{\partial\hat{\theta}^*}{\partial t}$, totally differentiating the first order condition (A.2) with respect to y, t, and $\hat{\theta}$ gives:

(A.4) $$(py^{*''} - c_1(y^{*'})^2 - c_1y^*y^{*''} - (c_2\theta + \xi)y^{*''} - cyy^{*''} + t^{*''})d\hat{\theta} - cy^{*'}dy + 0dt = 0.$$

Clearly, $\frac{\partial\hat{\theta}}{\partial t} = 0$ and when $y^{*'} = 0$, $\frac{\partial\hat{\theta}}{\partial y} = 0$. In equilibrium, the first order condition (A.2) must hold for $\hat{\theta} = \theta$. Totally differentiating (A.2) with respect to $\hat{\theta}$ at $\hat{\theta} = \theta$ yields

(A.5) $$(py^{*''} - c_1(y^{*'})^2 - c_1y^*y^{*''} - (c_2\theta + \xi)y^{*''} - cyy^{*''} + t^{*''} - c_2y^{*'} - cy^{'}y^{*'})d\hat{\theta} = 0.$$

Subtracting (A.4) from (A.5) gives:

$$cy^{*'}dy = (c_2 + cy^{'})y^{*'}d\hat{\theta}.$$

Thus,

(A.6) $$\frac{d\hat{\theta}}{dy} = \begin{cases} \frac{c}{c_2+cy^{'}} & \text{if } y^{*'} \neq 0 \\ 0 & \text{if } y^{*'} = 0 \end{cases}.$$

2. Strict concavity of the objective functions

Given the incentive compatibility constraints and the assumption that all the cross-partial derivatives are constant, the second order derivatives of Λ defined by equation (18) and Λ^* defined by equation (24) with respect to y and y^*, respectively, are the following:

(A.7) $$\Lambda_{yy} = -c_1 - \gamma\alpha b\theta\frac{d}{dy}(y^{*'}\frac{\partial\hat{\theta}}{\partial y}),$$

(A.8) $$\Lambda_{y^*y^*} = -c_1 < 0.$$

Since the optimal output scheme (y^*) is only a function of the true technology θ, $y^{*'}$, representing the rate of changes of the optimal output with respect to changes of θ, is independent of the variations of y in the process of maximizing the integrand (Λ) at any given θ. From (A.6),

$$\frac{d}{dy}(y^{*'}\frac{\partial\hat{\theta}^*}{\partial y}) = \frac{d}{dy}(\frac{y^{*'}c}{c_2 + cy^{'}}) = 0.$$

Substituting the above expression into (A.7) gives

$$\Lambda_{yy} = -c_1 < 0. \tag{A.9}$$

Hence, Λ is strictly concave in y and Λ^* is strictly concave in y^*.

3. Monotonicity and global implementability of the foreign output scheme

In this part, we will prove the monotonicity of the foreign government's output scheme so that a local implementable (incentive compatible) output scheme is also globally implementable. We will first prove this for a special case where foreign and domestic outputs are independent ($c = 0$), and then for the general case where $c > 0$.

If $c = 0$, from conditions (25) and (26), $p = c_1 y + c_2\theta + \xi + \gamma b\theta + cy^*$ so that the home government does not deviate from its non-cooperative perfect information best responses. However, $p = c_1 y^* + c_2\theta + \xi + \gamma^* b\theta + cy - \beta\frac{1-F}{f}c_2$ so that the foreign government still chooses a lower output for all firms below its non-cooperative perfect information best responses. Thus, asymmetric information works against the PHH.

Totally differentiating conditions (25) and (26) yields:

$$c_1 y' + c_2 + \gamma b = 0, \tag{A.10}$$

$$c_1 y^{*'} + c_2 + \gamma^* b - \beta\frac{d}{d\theta}\left(\frac{1-F}{f}\right)c_2 = 0. \tag{A.11}$$

Hence, if $-c_2 \geq \gamma b$, then since $\gamma > \gamma^*$ and $\frac{d}{d\theta}(\frac{1-F}{f}) \leq 0$,

$$y' = \frac{-c_2 - \gamma b}{c_1} \geq 0, \tag{A.12}$$

$$y^{*'} = \frac{-c_2 - \gamma^* b + \beta\frac{d}{d\theta}(\frac{1-F}{f})c_2}{c_1} > 0. \tag{A.13}$$

Also, $c_2 + cy' = c_2 - \frac{c}{c_1}(c_2 + \gamma b) = \frac{c_1 - c}{c_1}c_2 - \frac{c}{c_1}\gamma b < 0$.

To prove the monotonicity for the general case of $c > 0$, let $MC_y = c_1 y + (c_2\theta + \xi) + cy^*$ and $MC_{y^*} = c_1 y^* + (c_2\theta + \xi) + cy$. Rearranging conditions (25) and (26) yields:

$$c(p - MC_y - \gamma b\theta)y' - \alpha\gamma b\theta c y^{*'} = -c_2(p - MC_y - \gamma b\theta), \tag{A.14}$$

$$\beta\frac{1-F}{f}cy' = -(p - MC_{y^*} - \gamma^* b\theta) - \beta\frac{1-F}{f}c_2. \tag{A.15}$$

Applying the Cramer's rule, for $\theta < \bar{\theta}$,

$$y' = -\frac{f}{c\beta(1-F)}(p - MC_{y^*} - \gamma^* b\theta + \beta\frac{1-F}{f}c_2), \tag{A.16}$$

$$y^{*'} = -\frac{f}{\alpha\gamma b\theta c\beta(1-F)}(p - MC_y - \gamma b\theta)(p - MC_{y^*} - \gamma^* b\theta). \tag{A.17}$$

Also, $c_2+cy' = -\frac{f}{\beta(1-F)}(p-MC_{y^*}-\gamma^* b\theta)$ so that $(c_2+cy')y^{*'} = \frac{1}{\alpha\gamma b\theta c}(\frac{f}{\beta(1-F)})^2(p - MC_{y^*} - \gamma^* b\theta)^2(p - MC_y - \gamma b\theta)$. Since $(c_2 + cy')y^{*'} \leq 0$ from the local second order necessary condition for implementability, $p - MC_y - \gamma b\theta \leq 0$ so that the home production is either at or above the home government's non-cooperative perfect information best responses. If $p - MC_y - \gamma b\theta = 0$ at $\theta_1 < \bar{\theta}$, then $y^{*'}(\theta_1) = 0$. From (A.10), $y'(\theta_1) = -\frac{c_2+\gamma b}{c_1}$ so that $c_2 + c_1 y' = \frac{(c_1-c)c_2-c\gamma b}{c_1}$. Substituting this into (26) gives $p - MC_{y^*} - \gamma^* b\theta = -\beta\frac{1-F}{f}\frac{(c_1-c)c_2-c\gamma b}{c_1}$. Totally differentiating this gives $\beta\frac{d}{d\theta}(\frac{1-F}{f}) = 1 + \frac{\gamma^* bc_1}{(c_1-c)c_2-c\gamma b}$ at $\theta = \theta_1$. Since $\frac{d}{d\theta}(\frac{1-F}{f}) \leq 0$, $c_1 > c$, and $c_2 < 0$, $p - MC_y - \gamma b\theta = 0$ and hence $y^{*'}(\theta) = 0$ can hold at $\theta_1 < \bar{\theta}$ only if $c\gamma < c_1\gamma^*$ or $\gamma/\gamma^* < c_1/c$ so that $(c_1 - c)c_2 - c\gamma b < 0$.

From (26), $p - MC_{y^*} - \gamma^* b\theta = 0$ at $\theta = \bar{\theta}$. If $p - MC_{y^*} - \gamma^* b\theta = 0$ at $\theta_2 < \bar{\theta}$, then (26) gives $c_2 + cy' = 0$ so that $y' = -c_2/c$. Substituting $y^{*'} = 0$ into (25) gives $p - MC_y - \gamma b\theta = 0$. Hence, $y' = (-c_2 - \gamma b)/c_1 \neq -c_2/c$. Thus, $p - MC_{y^*} - \gamma^* b\theta \neq 0$ for all $\theta < \bar{\theta}$. From (A.16), $y'(\bar{\theta}) = 0$. Hence, totally differentiating (26) gives $\frac{d}{d\theta}(p - MC_{y^*} - \gamma^* b\theta) = -\beta\frac{d}{d\theta}(\frac{1-F(\theta)}{f(\theta)})c_2 < 0$. Thus, $p - MC_{y^*} - \gamma^* b\theta > 0$ so that $c_2 + cy' < 0$ for all $\theta < \bar{\theta}$. $p - MC_{y^*} - \gamma^* b\theta = 0$ and $c_2 + cy' = \frac{c_1-c}{c_1}c_2 - \frac{c}{c_1}\gamma b < 0$ at $\theta = \bar{\theta}$, which is consistent with the standard result that there is no distortion "at the top".[28]

From (A.17), $y^{*'} \geq 0$. From (14), $t^{*'} = -(p-MC_{y^*}-\gamma^* b\theta)y^{*'} \leq 0$. Since $t(\underline{\theta}) < 0$, all firms pay a tax ($t < 0$) that increases with θ. According to Chapter 7 in Fudenberg and Tirole (1991), Martimort (1992) and Stole (1991), $y^{*'} \geq 0$ is necessary and sufficient for global implementability under the single crossing condition $\pi_{y\theta} = -c_2 > 0$. Thus, the first order conditions (25) and (26) yield a pair of implementable output schemes for any given initial condition, provided $-c_2 \geq \gamma b$.

It is easy to check that, in a Nash equilibrium, the foreign government never chooses pooling for all firms, otherwise, the two first order conditions would give different values of y'. Moreover, if $y^{*'} = 0$ over an interval $\theta' < \theta < \theta''$, then $p - MC_y - \gamma b\theta = 0$ on (θ', θ''). Following the calculation in the case where $c = 0$, $y'' = 0$ on (θ', θ'') so that $y^{*'} = \frac{-c_2-\gamma^* b+\beta\frac{d}{d\theta}(\frac{1-F}{f})(c_2+cy')}{c_1} > 0$ at $\theta = \theta'$ and $\theta = \theta''$. Hence, the equilibrium foreign output increases for firms with a θ bigger than θ'' and decreases for firms with a θ less than θ'. Thus, the foreign government chooses a pooling equilibrium, i.e. $y^{*'} = 0$, only in a narrow interval of θ in Θ and only if $\gamma/\gamma^* < c_1/c$. Otherwise, $y^{*'} > 0$.

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[28] The H-type separating equilibrium in Bond and Gresik (2004), where $p - MC_{y^*} - \gamma^* b\theta = 0$ for firms with $\underline{\theta}$, does not exist here because the marginal social cost is lower for a firm with a higher θ by assumption so that, at its perfect information best responses, the foreign government always sees a higher extractable profit from firms with a higher θ .

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