TARIFFS AND THE ADOPTION OF CLEAN TECHNOLOGY UNDER ASYMMETRIC INFORMATION

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Abstract:

This paper examines the effect of import tariffs on the decision of a foreign monopolist to adopt "clean" technology – technology that reduces the flow of a negative cross-border externality per unit of exports. The clean technology is assumed to increase the marginal cost of production relative to the dirty technology, but only the firm knows the extent of the increase. Under complete information, we show that, despite its protectionist motivation, the importing country's optimal tariff induces the firm to adopt the clean technology if and only if it is globally efficient to do so. Under incomplete information, this efficiency property is disrupted. If the optimal tariff is decreasing in the marginal cost, then it leads the firm to bias its choice in favor of dirty technology.

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I. Introduction

Governments routinely impose unilateral trade restrictions on imported products to protect domestic residents from negative externalities. Such externalities may include threats to public health, safety, network compatibility or the environment, occurring anywhere along the supply chain from foreign production to home consumption. Often the externality can be mitigated at the point of origin by the adoption of an appropriate product design or production technique, herein called "clean" technology. Governments may promote clean technology by conditioning the terms of market access on its adoption. For example, a country might admit imports from firms or countries only if they meet certain health or safety standards, forgo certain inputs (e.g., child labor, hormones, genetically-modified organisms) or adopt environment-friendly techniques (e.g., fishing devices to reduce dolphin or sea turtle mortality).

The World Trade Organization (WTO) allows its members to use such trade restrictions, provided they are nondiscriminatory and do not constitute "disguised" protectionism.[1] However, as countries are not required to coordinate their policies or to compensate their trading partners for the terms-of-trade losses their externality-based trade restrictions inflict, it is often difficult to separate the terms-of-trade motive for such policies from their externality-reduction motive.[2] It is not surprising, therefore, that as more conventional forms of protection have been reduced over years, externality-based

[1]GATT Article XX (General Exceptions). More specific rules are found in the agreements on Sanitary and Phytosanitary Measures (SPS) and Technical Barriers to Trade (TBT). While product-based restrictions have always been legal under these provisions, recently the WTO Appleate body ruled that process-based restrictions are also legal.

[2]It is possible, under GATT Article XXIII.1(b), for a country seek redress for trade barriers not in violation of WTO rules; however, this provision is rarely used. Bagwell and Staiger (2001) make the case that WTO members should use non-violation complaints more regularly to control the terms-of-trade effects of environmental and labor policies.

trade restrictions have proliferated.[3] All of this raises the question of whether unilateral trade policy is an efficient means of promoting clean technology, when terms-of-trade motives are present.

Previous literature suggests that unilateral trade policy, *tariffs* in particular,[4] can indeed lead to the efficient adoption of clean technology. Ludema and Wooton (1994) show this in a two-country, non-cooperative policy game with cross-border pollution (flowing from foreign to home), in which governments employ both trade and pollution taxes. In equilibrium, the foreign country taxes pollution efficiently (thereby inducing foreign firms to adopt the proper techniques), despite its lack of concern for pollution *per se*. The reason is that cutting foreign emissions lowers the home optimal tariff, thus improving market access for foreign firms. In a similar vein, Copeland (1996) finds efficient foreign adoption when the home country optimally employs a "pollution-content tariff" (a tariff that varies with each unit imported according to the "dirtiness" of its production process).[5] Rather than operating through a foreign pollution tax, the tariff itself induces clean technology adoption as firms seek to improve their own market access. Thus an implication of the literature so far is that unilateral tariffs can be an

[3] For example, over 6000 new trade restrictions have been notified to the WTO by its members since 1995 under the TBT agreement alone (WTO, 2005).

[4] Markusen (1975) showed that a tariff is optimal unilateral policy in the presence of international pollution. He also showed that the combination of pollution-reduction and terms-of-trade motives leads to the over-taxation imports (relative to the Pigouvian prescription). Following in this tradition, we focus on tariffs here. As we will show, the tariff produces efficient technology adoption under complete information but not under asymmetric information. Thus, by using tariffs, we isolate the effect of the asymmetric information. Later on, we also compare our tariff results with standards and quotas.

[5] Copeland (1996) also shows that regulation of the production process by the foreign government creates rents that can lead the home government to over-tax foreign pollution as a rent-shifting tool. A similar result is found in Ludema and Wooton (1994) for the case of a process standard. The results are linked by the fact that a pollution-content tariff is equivalent to a simple tariff combined with a process standard.

effective environmental tool, even when it is driven in part by illegitimate (i.e., non-environmental) motives.[6]

The contribution of this paper is to show how these conclusions must be modified in the presence of asymmetric information.[7] We consider a model of a foreign firm that exports a good to the home country and, in the process, confers a negative externality on home residents. The firm has access to a clean technology, which, if adopted, reduces the externality at the expense of increasing the firm's marginal cost of production. The optimal policy for the home country in this context is a tariff, which is decomposable into an externality component that increases with the externality and a terms-of-trade component that usually decreases with the marginal cost of the firm. Under this policy, therefore, the firm secures improved market access by adopting the clean technology. With perfect information, this market access effect induces the firm to adopt the clean technology whenever it is efficient to do so, as in the previous literature. However, when only the foreign firm knows the marginal cost associated with the clean technology, we find that efficient adoption no longer holds. The reason is that adoption now signals that the firm's marginal cost under the clean technology is relatively low. This increases the terms-of-trade motive for a tariff and thereby counteracts the downward responsiveness

[6] Regibeau and Gallegos (2004) show a similar result when trade policy is used as a second-best method of controlling domestic pollution.

[7] Other papers considering cross-border externalities under asymmetric information include Ludema and Wooton (1997), Chang (1997), Bigano (2001), Engel (2004) and Furusawa, Higashida and Ishikawa (2004). The first four model the problem in a principal-agent framework, in which countries can sign binding contracts. Ludema and Wooton (1997) and Engel (2004) examine the choice between trade and environmental policies under adverse selection and moral hazard, respectively. Bigano (2001) considers harmonization of environmental policies in a federal system. Chang (1997) considers a signaling model (like ours) but with no trade policy. He finds a similar result to ours in so far as foreigners behave in an environmentally unfriendly manner to avoid signaling a low cost of pollution abatement. Furusawa, Higashida and Ishikawa (2004) consider non-cooperative trade policy toward a foreign monopolist under adverse selection (as we do); however, as they model clean technology as an endowment rather than a choice, there is no scope for signaling. Instead, they focus on the choice between tariffs and quotas.

of the tariff to the clean technology. The result is a bias against adopting the clean technology.

Although our model is couched in terms of an externality problem, the main result applies to technology-adoption problems more generally. In a setting without externalities but in which the foreign firm has access to a cost-reducing technology, a home optimal tariff would tend to deter investment, even without asymmetric information (see Choi, 1995, for example). Our model suggests that adding asymmetric information exacerbates this problem, because the decision to invest lowers the home government's belief about marginal cost by more than the actual cost reduction on average. This means that the optimal tariff increases more in response to investment (and hence is more of a deterrent) than would occur on average under complete information. Thus, the logic of our main result does not hinge on externalities. The reason we focus our paper on externalities is a practical one: it is one of the few areas in which unilateral trade policy is still permitted under the WTO, a circumstance bolstered by the presumption that unilateral trade policy is an effective means for promoting clean technology.[8] Anti-dumping and safeguards duties represent another form of relatively unfettered trade policy. Recent work by Crowley (2006) on the effect of these measures on technology adoption offers another potential application of our results.

Before moving to the model, we present a concrete example that illustrates the major points of our story. In 1989, the United States began requiring all domestic shrimp vessels to be equipped with turtle excluder devices (TEDs) – a technology that

[8] Without the externality element, the tariff would cause inefficient technology adoption even under complete information, so no one would advocate the use of tariffs as an efficiency-enhancing device in this case. With externalities, the argument for tariffs is at least plausible. Our point is that the argument does not survive the introduction of asymmetric information.

substantially reduces rates of sea turtle mortality in shrimp catches – and authorized the ban of imported shrimp from countries not adopting similar technology or not otherwise certified as safe.[9] The ban was extended to major Asian warmwater shrimp exporters in 1996, four of which (India, Pakistan, Malaysia, and Thailand) subsequently filed a dispute against the US with the WTO in 1997. The WTO found in 2001 that, although the US policy had flaws, the embargo could be maintained if implemented properly (WTO, 2001). By this time, most shrimp exporters[10] had either adopted TEDs or switched to safe methods, such as aquaculture, and US shrimp imports had begun to surge. In response, the US domestic shrimp industry in 2003 sought, and was granted, anti-dumping protection against several warmwater shrimp exporters (Brazil, Ecuador, China, India, Thailand, and Vietnam) (USITC, 2005). Interestingly, Thailand, along with other affected countries, later launched a another dispute against the US, charging that the US anti-dumping duties were too high, because they were not based on true measures of production costs but on "facts available" (i.e., unsympathetic guess work).

The basic elements of this case match up quite well with our model. The initial embargo on shrimp may be interpreted as a prohibitive tariff applying to imports under the dirty technology. That adoption of clean technology was met not with a return to the normal MFN tariff on shrimp but with an anti-dumping duty, based on facts available is also in keeping with our story.[11] Without more information, we cannot say if those

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[9] For example, some countries fish only in cold water where the risk of encountering sea turtles is small.
[10] Malaysia and India are notable exceptions. Costa Rica, Indonesia, Honduras, Nigeria, Thailand, Venezuela and had obtained certification but lost it by 2004 (USDOS, 2004)
[11] In principle, adoption of the clean technology should be met with a return to the WTO-agreed tariff, and thus the home government's discretion over its clean tariff may be limited. However, there are numerous ways the home government can affect market access after the adoption of clean technology. First, GATT tariff bindings only impose an upper limit on tariffs. Countries can and do maintain actual tariffs below bound rates, and this gives them a degree of discretion. Second, countries have discretion not to lower tariff bindings in subsequent negotiations. Third, countries can use anti-dumping duties, countervailing

countries that did not adopt turtle-safe methods were deterred by the prospect of being named in the anti-dumping case. Our paper, however, suggests that this is a distinct possibility.

The remainder of the paper is structured as follows. Section II describes the basic model, featuring a home government setting tariff policy toward a single foreign firm. Section III analyzes the complete information case. We find that, although trade is over-taxed due to the terms-of-trade motive, the firm follows the efficient decision rule in its adoption of clean technology. This serves as our benchmark. Section IV examines the case of incomplete information and establishes the main result. Section V considers several extensions of the basic model, allowing for alternative assumptions about market structure, timing, policy instruments and technology. We extend the model to Cournot duopoly, in which the foreign firm competes with a domestic firm, and to monopolistic competition with a continuum of foreign firms. We allow the home government to precommit to a tariff policy (contingent on the firm's technology choice) before the technology is chosen, and we consider a more general class of policies that includes standards and quotas. We examine the effect of a fixed cost to clean technology adoption and the effect of third markets. In general, we find that while the benchmark efficiency result under complete information may no longer hold, the addition of asymmetric information makes the adoption of clean technology less likely. Thus, our main result is fairly robust. Section VI concludes with some implications of these results.

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duties or safeguards, as in the Shrimp-Sea Turtle case. Finally, in Section V.B.2., we show that our main result also applies to the use of standards. It is entirely legal for a country to impose a high standard, so as to induce foreign firms to adopt the clean technology, and then impose an even higher standard once they have. We show that this is both optimal for the home country to do and produces the same deterrent effect as the optimal tariff.

II. The Model

We consider a partial equilibrium model of a country that imports a good from a foreign monopolist. We assume either that there is no domestic supply in this country or that the domestic industry is perfectly competitive, so that the demand for imports can be represented by a downward-sloping demand curve $p(x)$, where p is the domestic price and x is the quantity imported.

We assume that each unit imported generates a negative externality of v units of home utility. For our purposes, it does not matter whether the externality in question is generated by the foreign production of exports or by the home consumption of imports. For convenience of exposition, we assume that home production (if it exists) produces no externality, although this assumption is not necessary for our results. Because of the externality, the government of the home country has both a terms-of-trade motive and an externality-reduction motive for restricting trade. The policy it uses to restrict trade is taken to be a specific tariff t. Total home welfare is therefore

$$W \equiv \int_0^x p(x)dx - p(x)x + tx - vx \,. \tag{1}$$

The foreign firm produces x at a constant marginal cost of c, giving it an export profit function, $\pi \equiv p(x)x - (c+t)x$. The marginal cost depends on the firm's choice of technology, which we assume to be irreversible. Under the dirty technology, $c = c_0$ and $v = v_0$, whereas under the clean technology, $c = c_1 > c_0$ and $v = v_1 < v_0$. Letting

$k \equiv c_1 - c_0$ and $b \equiv v_0 - v_1$, we interpret k as the cost and b as the benefit of the clean technology, per unit of x.[12]

Before examining the behavior of the government and firm, let us consider the conditions for an efficient outcome. We are interested in efficiency from the standpoint of a world social planner, whose objective function is the sum of W and π, or

$$W + \pi = \int_0^x p(x)dx - (c + v)x \tag{2}$$

Maximization of (2) produces two efficiency conditions: (i) x should satisfy $p(x) = c + v$; and (ii) the clean technology should be adopted if and only if $b \geq k$. Condition (i) gives efficiency in production, while (ii) is the efficient technology-adoption rule. An outcome satisfying both of these conditions is called fully efficient.

III. Complete Information

This section examines the environmental effects of a unilateral tariff under complete information. The game is played in three stages: the firm makes its technology choice first; the government chooses its tariff second; and the firm chooses its level of exports third.

We begin by considering the firm's export choice, for a given technology and tariff. Profit maximization requires that marginal revenue be set equal to marginal cost plus the tariff:

$$MR(x) \equiv p'x + p = c + t. \tag{3}$$

We assume (3) has a unique solution $x = x(c + t)$.

[12] An implicit assumption here is that the foreign firm's technology choice applies only to its exports destined for the home market and not to any output destined for other markets. The case in which the technology choice applies to all output is discussed in Section V.C.

Next we consider the tariff-setting behavior of the home government. The government wishes to maximize home welfare, taking $x(c+t)$ into account. The first-order condition for welfare maximization is

$$W_t = x - [p'(x)x - t + v]x' = 0 \tag{4}$$

We assume $W_{tt} < 0$ for all t, so that the solution to (4) is the unique optimal tariff.

Total differentiation of (3) yields $x' = 1/MR'$, which allows us to rewrite (4) as an expression for the optimal tariff containing two familiar terms,

$$t = v + (p' - MR')x \tag{5}$$

reflecting the dual purpose of the tariff. The first term represents the standard Pigouvian optimal tax rule – that output be taxed according to the marginal external damage. Taken alone, this term would cause the firm to fully internalize the externality. The second term is the familiar Brander-Spencer (1984) optimal tariff toward a foreign monopolist, in the absence of externalities. This term is positive (negative) if the marginal revenue curve is steeper (flatter) than the demand curve. Substituting (5) into (3), we see that $p = c + v - MR'x$. Thus, under the optimal tariff, trade is unnecessarily restricted and full efficiency is not possible.[13] Nonetheless, it is still possible that the tariff will induce the firm to follow the efficient technology-adoption rule.

Finally, let us consider the firm's technology choice. The firm chooses the technology that minimizes its unit cost of production, taking into account the effect of the technology choice on the tariff. Thus it will choose the clean technology, if and only if, $t_0 \geq t_1 + k$.[14] Simply put, if the tariff under the dirty technology exceeds that under the

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[13] This is not entirely the fault of the tariff, as the monopoly power of the firm adds an additional distortion.
[14] To simplify the exposition, we assume that if the firm adopts the clean technology whenever it is indifferent between the two.

clean technology by more than cost of the clean technology, then the firm adopts the clean technology. This leads to our first main result:

Proposition 1: *With complete information, the firm adopts the clean technology if and only if* $b \geq k$. *Thus, the optimal tariff induces the firm to follow the efficient technology-adoption rule.*

Proof: With dirty technology, the tariff is determined by $x_0 - [p'(x_0)x_0 - t_0 + v_0]x_0' = 0$, where $x_0 = x(c_0 + t_0)$. With clean technology, the same condition can be written as $x_1 - [p'(x_1)x_1 - (t_1 + k) + v_0 + (k - b)]x_1' = 0$, where $x_1 = x(c_0 + t_1 + k)$. If $k = b$, the two equations have the same solution, $t_0 = t_1 + k$. Next, consider the derivative $\frac{d(t_1+k)}{dk}$. If this is positive, then for any $k > b$, it must be that $t_1 + k > t_0$, and likewise for any $k < b$, it must be that $t_1 + k < t_0$, as t_0 is invariant to k. Differentiation of (4) gives, $\frac{dt_1}{dk} = -\frac{W_{tk}}{W_{tt}} = \frac{x_1'}{W_{tt}} - 1$. Thus, $\frac{d(t_1+k)}{dk} = \frac{x_1'}{W_{tt}} > 0$, as $x_1' < 0$ and $W_{tt} < 0$ (the latter by the second-order condition for welfare maximization). QED.

Proposition 1 is illustrated in figure 1. The iso-cost line traces out the combinations of t_1 (the clean tariff) and k such that the firm is indifferent as to its choice of technology, given that t_0 (the dirty tariff) is set optimally by the government. It has a slope of –1. For any combination of t_1 and k above or to the right of this line, the firm strictly prefers the dirty technology, while below and to the left, the firm prefers the clean technology. The flatter line represents the optimal tariff under the clean technology. In general, this schedule may be nonlinear and may even slope upwards; however, it cannot be steeper than the iso-cost line (by the second-order condition). For any k to the right of the intersection of these two schedules, the optimal clean tariff is too high to induce the firm to choose the clean technology, and so it adopts the dirty technology. The opposite is true for k to the left of the intersection. It so happens that the intersection occurs at b, implying that the firm makes the efficient technology choice.

The reason the firm is indifferent between the two technologies when $k = b$ can be seen by inspecting equation (5). Suppose the second term in (5) is held constant. Then by adopting the clean technology, the firm can reduce the tariff by b. However, in so doing, the firm increases its marginal cost by k, so its effective marginal cost $c + t$ does not change. This justifies our supposition and also implies that the firm is indifferent between the two technologies.

IV. Incomplete Information

This section introduces incomplete information to the analysis of the previous section. It is now assumed that the cost of the clean technology k is private information of the firm. Let k be the realized value of a random variable drawn from a continuous distribution $F(k)$, with density $f(k)$ and support [0, K], where $b < K < \infty$. The home government knows F, but only the firm knows the true k, and all this is common knowledge.

Under these assumptions the effect of a tariff on the firm's technology decision is examined using the following signaling game. First, the firm learns the true cost k, and chooses its technology. Second, the home government, having observed the firm's decision, updates its beliefs about k, using Bayes' rule (if possible). It then sets the optimal tariff based on these beliefs. Finally, the firm chooses its level of exports, taking its technology and the tariff as given. The solution is a perfect Bayesian equilibrium.

Recall that if the firm adopts the dirty technology, then it does not incur k. In this case, k is irrelevant to the home government's tariff choice. The home government simply chooses t_0 to be the same as under complete information. Thus, if the firm adopts the dirty technology, the resulting profit of the firm and the welfare of the home country are the same as under complete information.

Suppose instead that the firm adopts the clean technology. The firm's optimal level of exports is $x_1 = x(c_0 + k + t_1)$. The level of k is now relevant to the home government's tariff choice, and the fact that the firm has chosen to adopt the clean technology may convey information about k that the government can use. Let $\phi(k)$ be the posterior density of k, if the firm adopts the clean technology. Expected home welfare is therefore

$$EW(t_1) \equiv \int_0^K \left[\int_0^{x_1} p(x_1)dx - p(x_1)x_1 + t_1 x_1 - v_1 x_1 \right] \phi(k)dk \tag{6}$$

Let τ denote the tariff that maximizes $EW(t_1)$.

Next consider the firm's technology choice. If the firm expects the government to impose τ, it will adopt the clean technology, if and only if, $k + \tau \le t_0$. In other words, there is a critical value $\kappa \equiv t_0 - \tau$, such that, if $k \le \kappa$, then the firm adopts the clean technology, and if $k > \kappa$, the firm adopts the dirty technology.

Given the firm's technology decision rule, the fact that firm chooses the clean technology implies that the probability of $k > \kappa$ is zero. Thus, if $\phi(k)$ is to satisfy Bayes' rule, it must be that

$$\phi(k;\kappa) = \frac{f(k)}{F(\kappa)} I_{[0,\kappa]}(k) \tag{7}$$

for $\kappa > 0$, where $I_{[0,\kappa]}(k)$ is the indicator function. That is, the posterior density is just the prior density truncated on the right by κ. For $\kappa = 0$, this is undefined, so $\phi(k;\kappa)$ may be any density on $[0, K]$.

Using (6), (7) and the definition of κ, we can summarize the equilibrium by the following two conditions:

$$\int_0^K \{x_1 - [p'(x_1)x_1 - \tau^* + v_1]x_1'\}\phi(k;\kappa^*)dk = 0 \tag{8}$$

$$\kappa^* = t_0 - \tau^* \tag{9}$$

Equation (8) is the first-order condition for the optimal tariff τ^*, given critical value κ^*. Equation (9) is a consistency condition, requiring that if $k = \kappa^*$, then the firm is indeed indifferent as to its technology choice.

Figure 2 illustrates an interior equilibrium. The iso-cost line now shows the critical cost κ for every clean tariff τ. The curve $\tau(\kappa)$ shows the tariff that maximizes expected welfare under the clean technology for every κ. Point A determines the equilibrium.[15] The horizontal line passing through A is τ^* as a function of the true cost k (τ^* is invariant to k because the government does not observe the true cost). This line is relevant to the behavior of the firm. If $k > \kappa^*$ ($k < \kappa^*$), then the firm's actual tariff-cost combination is some point on this line to the right (left) of point A. Such a combination would induce the firm to adopt the dirty (clean) technology.

[15] Without further restrictions on $f(k)$, we cannot rule out the possibility of multiple equilibria. This is not a problem, for all equilibria have the same efficiency properties relative to the complete-information benchmark. Thus, if there are multiple equilibria, the differences among them would be only in magnitude.

The next proposition establishes the relationship between the equilibrium critical value κ^* and the efficient critical value b.

***Proposition 2**: If $t_1(k)$ is decreasing for all k, then $0 < \kappa^* < b$. Thus, for all $k \in (\kappa^*, b)$, the firm adopts the dirty technology even though the clean technology is the efficient choice.*

Proof: Suppose $\kappa^* > 0$. If $t_1(k)$ is decreasing in k, then $W_{tk} < 0$. Thus, for any t_1 and $k < \kappa^*$, we have $W_t(t_1, k) > W_t(t_1, \kappa^*)$. Taking expected values gives

$$\int_0^K W_t(t_1, k)\phi(k; \kappa^*)dk > W_t(t_1, \kappa^*) \tag{10}$$

By equation (8), the left-hand side of (10) is equal to zero at $t_1 = \tau^*$, and hence, $W_t(\tau^*, \kappa^*) < 0$. Since $W_{tt} < 0$, it follows that $\tau^* > t_1(\kappa^*)$, where $t_1(\kappa^*)$ is the optimal complete-information tariff evaluated at κ^*. Using (9), we have $t_0 > t_1(\kappa^*) + \kappa^*$, which we know from the proof of Proposition 1 implies $\kappa^* < b$. Finally, suppose $\kappa^* = 0$. In this case, the inequality in (10) is reversed, and hence $\tau^* \leq t_1(0)$. From (5), we know that $t_0 > t_1(0)$ for $b > 0$, which implies that (9) cannot hold for $\kappa^* = 0$. Thus, $\kappa^* = 0$ is not an equilibrium for any beliefs. QED.

Proposition 2 can be explained with the help of Figure 3. Imagine a system of beliefs (contrary to Bayes' rule) in which the government assigns $k = \kappa$ with probability one, whenever the firm chooses the clean technology. In this case, the optimal tariff would be $t_1(\kappa)$, the complete-information optimal tariff under clean technology, which we know intersects the iso-cost line at b from our earlier analysis (point B in the diagram). Of course, such beliefs are silly. As long as there is the slightest probability that $k < \kappa$, then the government would wish to adjust its tariff. If the optimal tariff is decreasing in the marginal cost, the government would wish to adjust the tariff upwards. Thus, $\tau(\kappa)$ must be everywhere higher than $t_1(\kappa)$, except at $\kappa = 0$, and so $0 < \kappa^* < b$. This also means that if the firm's true cost is near b, it will find the clean tariff too high and will choose the dirty technology.

According to Proposition 2, there will be a bias against clean technology if the optimal complete-information tariff is decreasing in the marginal cost of production. Under what circumstances is the tariff decreasing in marginal cost? Total differentiation of (4) along with some manipulation yields that the tariff decreasing in marginal cost if and only if,

$$MR''(x) < -\frac{p'(x)}{x} \tag{11}$$

The right-hand side of (11) is positive, so the condition is satisfied as long as marginal revenue is not too convex.

V. Extensions

The results of the previous sections were derived for a model in which a foreign monopoly, facing a discretionary tariff, invests in technology that affects its marginal cost. In this section, we consider several extensions, allowing for alternative assumptions about market structure, timing, policy instruments, and technology. We find that both of our main propositions – efficient adoption with complete information, and underadoption with asymmetric information – are robust to alternative market structures and timing of the tariff. The efficient adoption result does not survive alternative policy instruments and technology (we knew that already), but the underadoption result survives in every case, except for the case of a quota, which gives an ambiguous result.

A. Market Structure

In this section, we consider some alternative market structures to check robustness. There are several alternatives that require no change in our thinking at all. For example, we could assume competitive foreign producers with a foreign government that regulates exports and pollution, as in Ludema and Wooton (1994). Such model is isomorphic to the foreign monopoly model, the key point being that the cost of the home tariff, which is borne by the *industry*, and the cost of the clean technology, which is borne by the *firm*, are internalized by a single decision-maker.

1) Cournot Duopoly

A market structure to which our results do not obviously extend is that of the foreign firm competing in quantities with a domestic firm in the home market. The concern is that foreign adoption of clean technology signals a low foreign marginal cost not just to the home government but also to the home firm. As outputs are strategic substitutes, the home firm would respond by reducing its output, which benefits the foreign firm. Thus, asymmetric information may actually *encourage* clean technology through this effect. Here we show that, at least in the case of linear demand, this effect does not outweigh the home tariff effect, and thus asymmetric information continues to discourage clean technology.

Suppose there are two firms, home and foreign, competing in the home market. The home firm produces no pollution and has a known marginal cost c^h. As before, foreign marginal cost c^f equals c_0 under dirty technology and $c_0 + k$ under clean technology. Demand is assumed linear: $p = \alpha - \beta(x^h + x^f)$, $\alpha, \beta > 0$.[16] The timing is as follows: (1) the foreign firm chooses its technology; (2) both the home firm and home government update their beliefs about foreign marginal cost; (3) the home government sets the tariff; and (4) Cournot competition takes place.

Profit of the firms are given by $\pi^h = (p - c^h)x^h$ and $\pi^f = (p - t - c^f)x^f$, and home welfare by, $W = \int_0^{x^h + x^f} pdz + \pi^h + (t - v)x^f$. The efficient technology adoption rule is for the foreign firm to adopt the clean technology if and only if $b \geq k$.

With complete information, the Cournot outputs, given tariff *t*, are,

$$x^h = \frac{\alpha - 2c^h + t + c^f}{3\beta}, \quad x^f = \frac{\alpha + c^h - 2(t + c^f)}{3\beta} \tag{12}$$

Using these in W and solving the optimal tariff gives, $t = \frac{4\alpha - 2c^h - 5c^f + 6v}{11}$, which gives an equilibrium level of foreign profit of,

$$\pi^f = \frac{1}{\beta}\left[\frac{\alpha + 5c^h - 4(c^f + v)}{11}\right]^2. \tag{13}$$

It is clear from (13) that clean technology produces higher foreign profits whenever $b > k$. Thus the optimal tariff under complete information induces efficient technology adoption, just as in the case of foreign monopoly.

[16] This demand function satisfies condition (11).

With incomplete information, the home firm maximizes expected profits, $E_{\phi}(\pi^{h}) = \{\alpha - \beta[E_{\phi}(x^{f}) + x^{h}] - c^{h}\}x^{h}$, with the expectation taken over posterior beliefs. This gives equilibrium output levels in the (Bayesian) Cournot Nash equilibrium of,

$$x^{h} = \frac{\alpha - 2c^{h} + t + E_{\phi}(c^{f})}{3\beta}, \quad x^{f} = \frac{\alpha + c^{h} - 2(t + c^{f})}{3\beta} + \frac{c^{f} - E_{\phi}(c^{f})}{6\beta}. \tag{14}$$

Comparing (14) to (12), we see that home output under asymmetric information is a best response to the expected output of the foreign firm, whereas foreign output depends on both the actual cost and home's expectation of that cost. Note that foreign output, and thus foreign profit, is decreasing in $E_{\phi}(c^{f})$. Thus, other things equal, the foreign firm would want to over-adopt clean technology as a way to manipulate the home firm into believing that its marginal cost is lower than it really is.

The countervailing effect comes from the tariff. Using (14) in W enables us to find the optimal tariff, $\tau = \frac{4\alpha - 2c^{h} - 5E_{\phi}(c^{f}) + 6v}{11}$, which gives equilibrium foreign profits of,

$$\pi^{f} = \frac{1}{\beta}\left[\frac{\alpha + 5c^{h} - 4\left(c^{f} + v\right)}{11} - \frac{3\left(c^{f} - E_{\phi}(c^{f})\right)}{22}\right]^{2}. \tag{15}$$

Evidently, the negative effect of $E_{\phi}(c^{f})$ on the tariff is enough to make foreign profit increasing in expected cost. The underadoption result follows directly. If the foreign firm follows the efficient decision rule, it minimizes $c^{f} + v$, thus maximizing the first term in (15). However, given this rule, the home government and firm will expect the additional cost $E_{\phi}(k)$ to less than b whenever the foreign firm actually adopts clean technology. But this means that the second term in (15) must be positive for any foreign firm whose actual k is near b. Thus, any firm whose actual k is sufficiently near b will not adopt the clean technology.

2. Many Foreign Firms

Up to this point, we have considered only cases in which a single entity, the foreign firm, makes the choice of technology adoption. In this section, we extend our results to a case of many foreign firms, each with a clean technology cost independently drawn from F. The concern is that the technology choice of an individual firm has no affect on the home government's belief about the average marginal cost of the population as a whole and thus may not affect the policy. This turns out to be irrelevant. The key to our results is not that individual firms affect beliefs; it is that asymmetric information permits the home government to differentiate between firms only by their choice of technology and not by their actual marginal cost.

We assume a continuum of firms, each producing a unique variety of a differentiated product. Utility of the home consumer is given by the functional,

$$U(x) = \alpha \int_0^1 x(z)dz - \frac{1-\beta}{2} \int_0^1 x(z)^2 dz - \frac{\beta}{2}\left(\int_0^1 x(z)dz \right)^2 + y \tag{16}$$

where $\alpha > 0$, $0 \le \beta < 1$, $x(z)$ is consumption of variety z and y is consumption of a freely traded numeraire. The budget constraint is $I \ge y + \int_0^1 p(z)x(z)dz$. A convenient feature of (16) is that utility maximization produces a linear demand for the differentiated product, $X = \alpha - P$, where $X \equiv \int_0^1 x(z)dz$, $P \equiv \int_0^1 p(z)dz$, and a linear demand for each variety,

$$x(z) = \alpha + \frac{\beta}{1-\beta} P - \frac{1}{1-\beta} p(z). \tag{17}$$

The degree of substitutability among varieties is captured by the parameter β.

Each firm z has a marginal cost $c(z)$, faces a tariff $t(z)$ and generates per unit pollution $v(z)$. Given these values, each firm sets its price according to,

$$p(z)=\frac{1}{2}\left[\alpha(1-\beta)+\beta P+c(z)+t(z)\right]. \tag{18}$$

Integrating (18) allows us to solve for P, as a function of $C\equiv\int_0^1 c(z)dz$ and $T\equiv\int_0^1 t(z)dz$, and thus compute output and profits of each firm, aggregate output, and welfare:

$$x(z)=\frac{\alpha-\beta X-c(z)-t(z)}{2(1-\beta)} \tag{19}$$

$$\pi(z)=(1-\beta)x(z)^2 \tag{20}$$

$$X=\frac{\alpha-C-T}{2-\beta} \tag{21}$$

$$W=\frac{\beta}{2}X^2+\frac{1-\beta}{2}\int_0^1 x(z)^2dz+\int_0^1\left[t(z)-v(z)\right]x(z)dz \tag{22}$$

Prior to its technology choice, each firm receives an independent draw from the distribution F to determine its marginal cost of production under the clean technology. To keep the problem as transparent as possible, suppose there are only three possible outcomes: high cost, low cost and medium cost, each occurring with positive probability. Assume the high cost is so high that clean technology is never profitable and the low cost is so low that it is always profitable. The only question remaining is whether medium-cost firms adopt clean technology. Assume the medium cost is a known value c_0+k, where $k\in(0,b)$, i.e., clean technology is efficient. Finally, let μ_0 denote the fraction of all firms that choose the dirty technology (i.e., all high-cost firms plus the medium-cost firms that do not adopt the clean technology), and let μ_L and μ_M denote the fractions of the firms that use the clean technology and are low and medium cost, respectively.

With complete information, the home government can charge a different tariff on each foreign firm, based on the firm's technology choice and marginal cost.[17] Thus, there are three different tariffs to consider, one for the dirty technology and one for each to the two types adopting the clean technology. We rewrite the welfare function as,

$$W = \frac{\beta}{2} X^2 + \frac{1-\beta}{2} \sum_{i=0,L,M} x_i^2 \mu_i + \sum_{i=0,L,M} (t_i - v_i) x_i \mu_i \tag{23}$$

for i = 0, L, M, where we note $v_L = v_M = v_1$. Differentiating (23) using (19) and (21) gives optimal tariffs implicitly defined by,

$$t_i = v_i + (1-\beta)x_i - \beta X + \frac{\beta}{2-\beta}\left[X + \sum\nolimits_{j=0,L,M} (t_j - v_j)\mu_j\right] \tag{24}$$

Substituting (24) into (19), we can express the difference in output between a medium-cost firm under clean technology and a firm under dirty technology as,

$$x_M - x_0 = \frac{1}{1-\beta}(b-k) \tag{25}$$

As there is a one-to-one relationship between profits and output, it follows that a medium-cost firm strictly prefers the clean technology if $b > k$. Thus, once again we have efficient technology adoption.

Under incomplete information, the home government can differentiate between firms only by their choice of technology. Thus, it chooses only two tariff levels, t_0 and t_1, applying to firms with dirty and clean technology, respectively. Mathematically, the only alteration necessary to the above analysis is that now we impose the constraint $t_L = t_M = t_1$ on the maximization of welfare (23). The optimal tariff for dirty firms remains unchanged. The optimal tariff on clean firms satisfies,

[17] In general, tariff discrimination on the basis of marginal cost would run amok of WTO rules, though discrimnation is permitted under anti-dumping rules. If we restrict the home government to discriminating only the basis of the choice of technology, then the outcome is the same as under asymmetric information.

$$t_1 = v_1 + (1-\beta)\frac{\mu_L x_L + \mu_M x_M}{\mu_L + \mu_M} - \beta X + \frac{\beta}{2-\beta}\left[X + \sum\nolimits_{j=0,L,M}(t_j - v_j)\mu_j\right] \qquad (26)$$

Comparing the second term in (26) with (24) we see that the optimal tariff now depends on the expected cost of the medium and low cost firms, rather than actual cost. The difference in output between a medium-cost firm under clean technology and a firm under dirty technology can be written as,

$$x_M - x_0 = \frac{1}{1-\beta}(b-k) - \frac{\mu_L}{\mu_L + \mu_M}(x_L - x_M) \qquad (27)$$

The second term in (27) is positive, because low-cost output exceeds medium-cost output facing the same tariff. Thus, if $b-k$ is small enough, the right-hand (27) must be negative for any μ_M, implying that is unprofitable for a medium-cost firm to adopt the clean technology.

The intuition is straightforward. Faced with the inability to distinguish low-cost from medium-cost clean technology adopters the government chooses it tariff somewhere in between the optimal tariffs of the two types. If the medium cost is high enough, this implies a clean tariff that is too high for the medium-cost firms to be willing to adopt the clean technology.

B. Policies

In this section, we investigate some alternative assumptions about the policies available to the government. Two strong assumptions made in previous sections were that the government's action takes place after the firm's technology choice and that the government uses a tariff. In some cases, however, it may be possible for the government to set a policy before the technology choice, specifying the terms of market access contingent on technology. Moreover, in reality, it is quite common for governments to use standards, rather than tariffs, as a means of controlling externalities associated with imports. This section explores these possibilities.

1. Commitment

In previous sections, we have shown that underadoption of clean technology occurs essentially because, with asymmetric information, the gap between the optimal tariff under dirty technology and that under clean technology, $t_0 - t_1$, is too small. Now suppose the government can choose its tariff policy (specifying its tariff as a function of the firm's technology) before the firm's technology choice. In other words, the government can commit to a gap $t_0 - t_1$. Would the home government choose the gap so as to eliminate underadoption?

In general, the answer is, no. The government does have an incentive *ex ante* to increase the gap, so as to increase the likelihood of adoption. However, it is not optimal to completely eliminate the inefficiency, because a small deviation from efficient adoption has a second order welfare effect, while moving the tariffs in the direction of optimal *ex post* tariffs causes a first-order increase in welfare. Thus, the tariff gap $t_0 - t_1$ with commitment would be larger than without commitment, but still there would be underadoption. Thus, we see that the basic problem is not one of commitment but again the inability of the home government to tax imports according to the realized value of the firm's marginal cost.

2. Standards

Next, we consider a more general class of policies than a tariff. Suppose the home government can require that the foreign firm pay an amount *t* per unit imported, and that this policy contributes to home welfare by an amount $g(t)x$, where $g'(t) \geq 0$. In the special case of $g(t) = t$, we interpret t as a tariff and $g(t)x$ as tariff revenue. Alternatively, we might think of t as an externality-abatement expenditure necessary to satisfy a home product (or process) standard, with $g(t)x$ as the resulting reduction in the externality. Following this interpretation, assume $g(t)$ is strictly concave, $g(0) = 0$, and $\lim_{t \to \infty} g(t) = v_1$. Welfare of the home government is given by,

$$W \equiv \int_0^x p(x)dx - p(x)x - [v - g(t)]x \tag{28}$$

As before, the foreign firm can adopt either dirty ($c = c_0,\ v = v_0$) or clean ($c = c_1,\ v = v_1$) technology, where c is marginal cost and v is gross externality. Maximizing (28) results in an optimal standard satisfying,

$$g(t) = v + [p' - g'(t)MR']x \tag{29}$$

Like the tariff, the optimal standard is set above the efficient level because of its effect on the terms of trade. This is reflected in the second term in (29). This term must be negative, which implies $g'(t) < 1$, whereas world efficiency would call for a standard satisfying $g'(t) = 1$.[18] Unlike an optimal tariff, the optimal standard does not lead to efficient technology adoption, even under complete information. This is because the cost to the firm t is nonlinear in v. Nevertheless, asymmetric information continues to cause underadoption of the clean technology relative to the complete information case if t is decreasing in c. Intuitively, only a firm whose marginal cost under the clean technology is relatively low will adopt. Thus, if t is decreasing in c, the observation that the firm has

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[18] That is, the marginal cost of abatement equals the marginal benefit from reducing the externality.

adopted will trigger an increase in the standard, and this will deter all but the lowest cost firms.

It can be shown that condition (11), the necessary and sufficient condition for the tariff to be decreasing in marginal cost, is also sufficient for the standard to be decreasing in marginal cost. Thus, there are no change in the results for the case of a standard.

3. Quotas

Another case to be considered is that of $g(t) = 0$. This can be thought of as a standard with no abatement, a tariff with no revenue, or simply a quota. In this case, the home welfare function is U-shaped, so that the home optimal policy is either free trade or autarky, depending on parameters. Autarky is preferred if v is sufficiently high relative to the free trade level imports. As with the standard, the optimal quota generally does not lead to efficient adoption even under complete information. Under asymmetric information, we might expect to see overadoption of clean technology relative to complete information, given that the home government is *less* likely to impose autarky the lower is foreign marginal cost. However, the quota is such a blunt instrument that the effect of asymmetric information turns out to be ambiguous.

To illustrate, assume the foreign firm's marginal cost under the clean technology can take on one of two values, high or low. Assume also that adoption of the clean technology involves a very small fixed cost, so that the firm prefers dirty technology in autarky. Finally, assume the home government's optimal complete-information policy is: choose free trade whenever the firm adopts the clean technology and has low cost, and choose autarky otherwise.

Under asymmetric information, if the probability that the firm has low cost is sufficiently high, the government will choose free trade whenever the firm adopts clean technology. Thus, the firm always adopts the clean technology regardless of marginal cost, and we can say that asymmetric information leads to overadoption relative to complete information. If, however, the probability that the firm has low cost is low, the home government will choose autarky regardless of the technology choice of the firm. In this case, the firm will never adopt the clean technology, and asymmetric information will have caused underadoption relative to complete information. Thus, the effect of asymmetric information on the likelihood of clean technology adoption is ambiguous in the case of a quota.

C. Technology

Throughout the paper, we have assumed that clean technology increases only the marginal cost of foreign exports to the home country. Yet it is possible that clean technology might also involve non-negligible fixed costs or increase the marginal cost of foreign output destined for other markets. These costs have no effect on the home optimal tariff. They do, however, make it more costly for the foreign firm to adopt clean technology and thus are likely to disrupt efficient technology adoption under complete information.[19] Under asymmetric information, our results do no change, so long as these other costs are not strongly inversely correlated with marginal cost of foreign exports to the home country. As long as the marginal cost under the clean technology is lower on

[19] Indeed, the possibility of exports to third markets has been one of the main criticisms of the use of unilateral trade policy for environmental purposes in the area of tropical timber.

average for firms that adopt than for those that do not and the optimal tariff declines with expected marginal cost, the underadoption result goes through.

VII. Conclusions

We conclude this paper with a discussion of some implications of our results for the rules governing externality-based trade restrictions in the WTO. The first rule of the WTO is non-discrimination. Generally speaking, it is unacceptable for a country to impose different tariffs on different countries exporting the same product, just because they use different technologies. Choi (1995) uses a model similar ours, except with complete information and no externalities, to show that this non-discrimination rule promotes the adoption of cost-reducing technology, because the alternative—discriminatory tariffs—tends to penalize low cost firms.

GATT Article XX allows for an exception to the non-discrimination rule. It allows a country to discriminate between countries and firms based on technology, so long as the technology is linked to externalities. It turns out this link makes a lot of difference, as has been shown in previous literature and as we confirm in Proposition 1: when technology is linked to externalities (and information is complete), discrimination may lead to efficient adoption. Moreover, even when efficient adoption is violated, as in some of the extensions considered in Section V, there is no general conclusion that there will be too much or too little adoption, whereas a prohibition on technology-based discrimination would almost certainly cause underadoption. Thus, on the basis of these considerations, it would appear that Article XX is a good, if not perfect, exception to the rule of non-discrimination.

By introducing asymmetric information, our paper highlights another dimension of the discrimination issue. The inability of the home government to observe the cost associated with the clean technology means that it can *only* discriminate on the basis of technology and not on the basis of marginal cost. Hence, upon adopting the clean technology, a relatively high cost firm faces the same tariff as a low cost firm. Because this tariff is based upon the expected cost of the firm, it is too high for the high cost firm, and thus the high cost firm is deterred from adopt the clean technology. This is the main result of our paper, and it is quite robust.

It is important note, however, that asymmetric information is only one possible factor preventing the home government from discriminating on the basis of marginal cost. Existing WTO precedent on Article XX also prevents this: discrimination on the basis of technology is permitted only to the extent that the technology affects the externality, not marginal cost. Thus, we may expect the underadoption problem identified in this paper to apply even to complete information settings with heterogeneous firms (as in Section V.A.2).

Moreover, it becomes clear that the current implementation of Article XX is flawed. Preventing discrimination on the basis of marginal cost does not prevent externality-based trade restrictions from being influenced by terms-of-trade considerations. Rather it introduces a conflict between the externality-reduction and terms-of-trade motives for a tariff. By reducing the externality, foreign adoption of the clean technology reduces the externality-reduction motive for a tariff. The resulting tariff reduction is what gives the firm the incentive to adopt clean technology. Preventing cost discrimination causes the terms-of-trade motive to interfere with this mechanism. Of course, if the underlying problem is one of asymmetric information, then even lifting the ban on cost discrimination will not help. Here the solution is to attack the terms-of-trade motive directly, as suggested by Bagwell and Staiger (2001), or focus on cooperative information-revelation mechanisms, as in Ludema and Wooton (1997).

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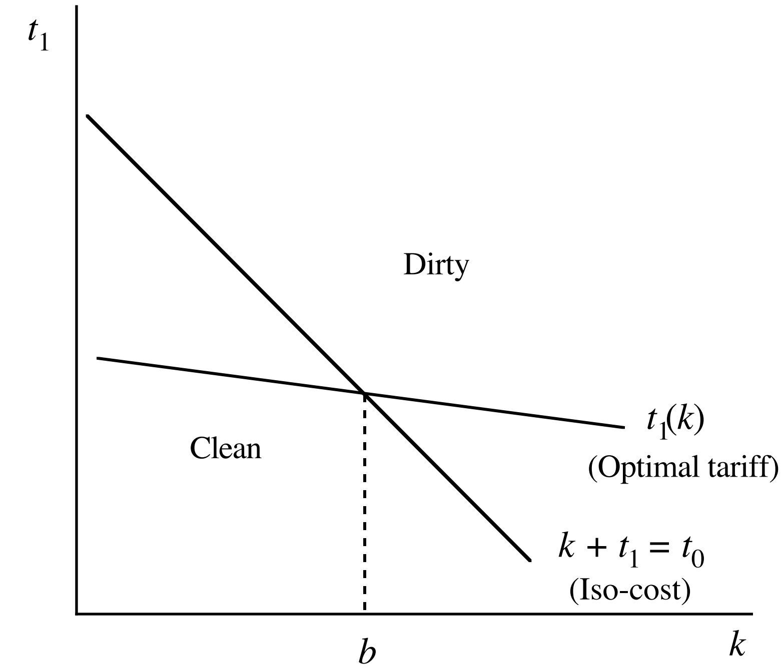

Figure 1: Environmental Efficiency with Complete Information

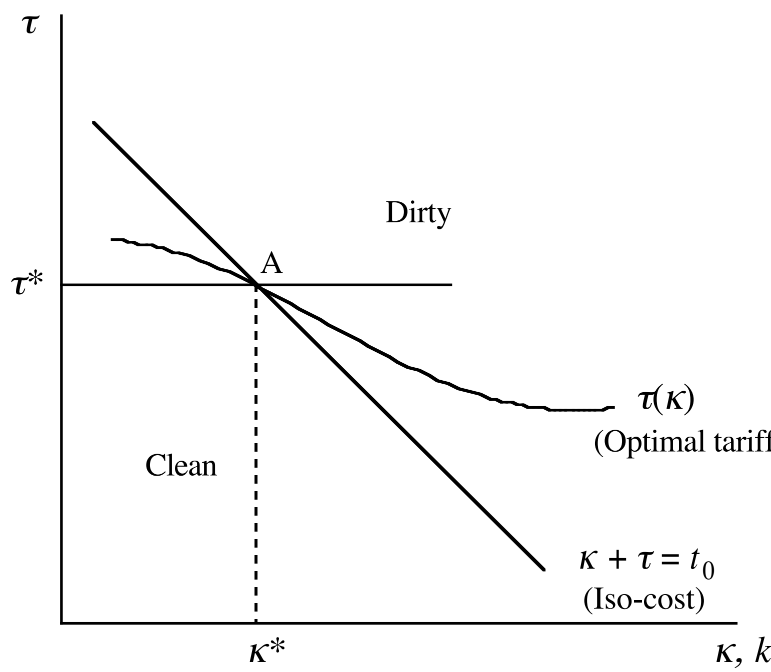

Figure 2: Equilibrium with Incomplete Information

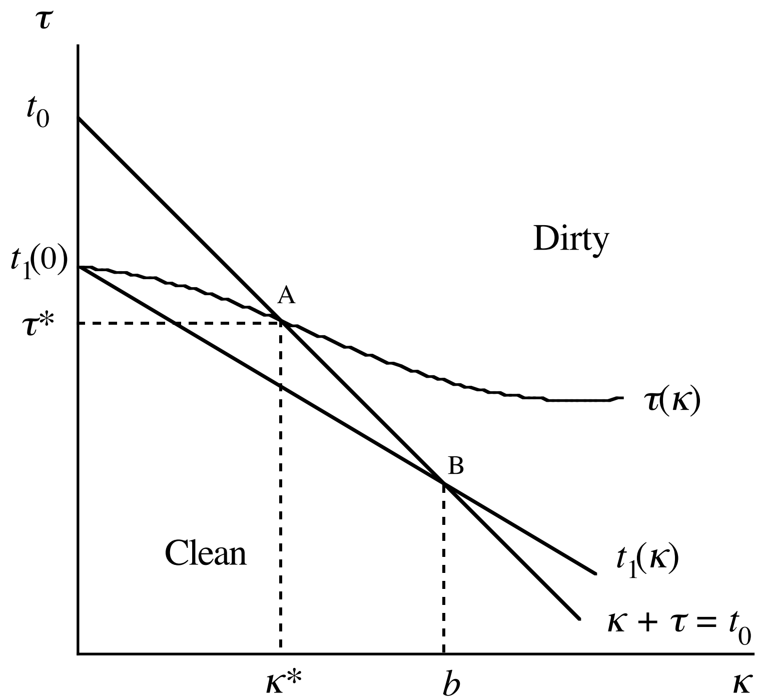

Figure 3: Tariff-induced Bias Against Clean Technology under Incomplete Information