Environmental Policy, R&D and the Porter Hypothesis in a Model of Stochastic Invention and Differentiated Product Competition by Domestic and Foreign Firms

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Abstract

We study a model of differentiated product competition by domestic and foreign firms that compete for the domestic market and invest in environmental R&D in order to reduce costs of complying with government pollution standards. In this setting, we find that optimal standards may often satisfy the "Porter Hypothesis" in two senses: (1) environmental standards that maximize post-innovation (ex-post) domestic welfare may be tighter than their globally optimal counterparts; and (2) in order to spur domestic R&D, government regulators may optimally commit (ex-ante) to pollution abatement standards that exceed their ex-post optimal levels.

Keywords: Environmental policy, innovation, R&D, Porter hypothesis, imperfect competition.

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Environmental Policy, R&D and the Porter Hypothesis in a Model of Stochastic Invention and Differentiated Product Competition by Domestic and Foreign Firms

Controversy continues to rage in the environmental economics community about the merits of the "Porter Hypothesis." In his landmark articles (Porter, 1990, 1991; Porter and van der Linde, 1995), management guru Michael Porter argues that tight environmental regulations can spur technological innovation that is not only beneficial to the environment, but also enhances industry competitiveness. Indeed, Porter argues that a Nation's domestic producers may be advantaged by tighter environmental regulations than foreign governments impose on their international rivals. Rightly or wrongly, Porter's "hypothesis" has also been interpreted to claim that "tight" environmental policy – tighter than Pigovian regulation – enhances economic welfare even when ignoring international trade (e.g., Ambec and Barla, 2002; Mohr, 2002). These claims have spurred both scathing criticisms from economists skeptical that imposing costs on industry can be justified as good industrial policy (Palmer, et al., 1995; Economic Report of the President, 2004, p. 177) and a growing academic literature that identifies potential economic rationales for "tight" environmental regulation. In this paper, we interpret the "Porter Hypothesis" broadly to endorse "tight" environmental standards relative to specific benchmarks that we identify.

The Porter Hypothesis appears to have had considerable influence in both the private sector (Heyes and Liston-Heyes, 1999) and policy circles. For example, China has been strikingly aggressive in tightening automobile emissions standards for its market. In just ten years (from 2000 to 2010), China will have gone from virtually unregulated vehicle emissions to standards that rival Europe's, among the strongest in the world. By 2010, China will have tightened its limits on automotive emissions of carbon-monoxide (CO), hydrocarbons (HC) and nitrous oxides (NOx) to between one-fourth (for CO) and one-sixth (for HC and NOx) the levels allowed when it first adopted European standards in 2000. With fewer than twenty cars per thousand population in China today, these changes have surprised some international observers. For example, industry experts Lee Schipper and Wei-Shiuen Ng write (October 18, 2004): "At the time U.S. or Europe had such low penetration of motor vehicles, emissions standards did not exist."

Perhaps the case of Chinese auto emission standards, among others, can be understood as an application of the Porter Hypothesis, broadly interpreted, with tight environmental regulations somehow imparting an advantage to China's domestic automobile industry relative to its international competition, potentially due to resulting incentives for research and development (R&D). In this paper, we seek to investigate this proposition in a model that is consistent with the Chinese experience in the following respects. First, in the domestic market to which environmental regulations apply, both domestic and foreign producers compete in differentiated products. Secondly, environmental standards apply to all producers in the domestic market, both domestic and foreign. Thirdly (and crucially), both domestic and foreign producers can invest in R&D that may ultimately reduce costs of complying with environmental regulations. We investigate a model of differentiated product competition and stochastic invention that has these features.

Two key issues arise in this setting. First, because the domestic government may be concerned with the welfare of its own people and its own producers, but not the profits of international competitors, its regulatory choices may diverge from those of a "global planner" that maximizes overall economic welfare to all affected agents (including foreign firms). For example, for given technological outcomes, will (and when will) a domestic planner wish to set tighter environmental standards than his global counterpart? In addressing this question, we build on some closely related work of Brian Copeland (2001). Copeland (2001) shows that a domestic government may wish to set an environmental standard that is tighter than globally optimal when the domestic industry has a sufficiently large advantage in its pollution-abatement / environmental-compliance technology. We find that, even without a technological advantage (and also with one), tighter standards are favored by the domestic planner.

Second, even without explicit market failures in the research sector (such as the knowledge spillovers studied by Hart (2004) or the learning-by-doing externalities modeled by Mohr (2002)), environmental policy may not deliver socially optimal incentives for research, even when it delivers socially optimal environmental outcomes for any given set of technologies. The reasons are well known to students of environmental innovation: Even when environmental policy gets the margins right for given technologies, it need not confront firms with the exact differences in social welfare created by different technology outcomes. Given differences between private R&D incentives and their societal counterparts – and absent an ability to directly regulate R&D (due to the inherent unobservability of R&D expenditures) – the government may want to modify its environmental policies in order to spur more or less R&D than would otherwise occur. Of course, the nature of these effects depends crucially on the environmental policy instrument that is employed (e.g., see Fischer, Parry and Pizer, 2003). In this paper (like Copeland, 2001), we restrict attention to environmental standards, the regulatory tool of environmental policy most widely used in practice. We find that a domestic planner would like to spur higher R&D from the domestic industry, and lower R&D from its foreign competition, than occurs under standards that are chosen optimally for given technology outcomes. For a number of reasons, we cannot make general statements about how the government will want to go about providing incentives for these changes in R&D. However, a numerical illustration indicates that broadly tightened environmental standards will, for the array of cases examined, provide the enhanced R&D incentives desired by both domestic and global planners. For the numerical examples considered, the Porter Hypothesis is thus broadly supported in the sense that domestic (global) welfare is maximized by committing to an array of technology-contingent standards that are mostly higher than ex-post optimal counterparts.

In the literature, several other arguments have been put forth in support of some version of the "Porter Hypothesis." First (and most prominent in the literature) is the proposition that, through various different mechanisms, a tight domestic environmental policy may raise the relative marginal production costs of international rivals, vis-à-vis those of a large domestic firm. In these strategic trade models of imperfect competition, tight environmental policy serves as an implicit export subsidy which, by the logic of Brander and Spencer (1985), increases market share of the domestic firm and thereby increases domestic firm profit. Greaker (2003) proposes the most direct mechanism for this effect, arguing that the environment may be an inferior input in production; if so, a stricter environmental policy (for the domestic firm) directly lowers the firm's marginal production costs. Greaker (2006) proposes a different mechanism, with stricter domestic environmental policy yielding a "greener" intermediate input for which the domestic industry has a superior production technology. Most closely related to Porter's conjecture – and hence, of most relevance for the present paper – is a mechanism proposed by Simpson and Bradford (1996) that explicitly incorporates technological innovation.[1] In their model, a firm's research and development (R&D) reduces both its pollution abatement costs and its marginal production costs; a strict environmental policy, by stimulating domestic R&D, may potentially advantage the domestic firm with its resulting lower production cost. However, the authors conclude that this outcome is a possibility, "not a general result," and that "it is unlikely that it (environmental regulation) will serve to generate industrial advantage."

Second, ignoring international trade, a series of interesting papers focuses on whether tight environmental policy can increase economic welfare in the presence of various other market failures. Ambec and Barla (2002) argue that firms may suffer from an agency problem which impedes incentives for environmental R&D; environmental regulation can mitigate the agency problem, promoting more R&D. Mohr (2002) posits a "learning-by-doing" externality associated with the adoption of a new "clean" technology; with this externality, the government can increase welfare by promoting the adoption of the new technology with strong environmental policy. Hart (2004) argues that environmental taxes can increase economic growth by spurring R&D that is otherwise underprovided due to knowledge spillovers.

Third, a set of papers identify positive predictions that are arguably consistent with some interpretations of the Porter Hypothesis. Xepapadeas and de Zeeuw (1999) show that tighter environmental policy can increase average productivity by spurring a

[1] See also related papers by Ulph (1996), Conrad (1993), and Barrett (1994).

reallocation of capital from older (less productive) to newer (more productive) assets; however, the tighter policy does not benefit the firms, which obtain lower profit overall. Popp (2005) shows that when R&D outcomes are random, outcomes from policy-induced R&D can sometimes be so good that the firm benefits from the research can exceed the costs of the environmental regulation (the "complete offset" that some have interpreted Porter to have claimed). However, the environmental regulation still reduces firm profits on average.

This paper differs quite sharply from these prior literatures. Unlike the third set of papers (and like the second), we focus on normative versions of the Porter Hypothesis, namely, optimal policies. Unlike the second, we do not invoke any explicit market failures, whether agency problems, knowledge spillovers, or learning-by-doing externalities, to motivate environmental regulation. Like the first set of papers (and unlike the second), we model imperfect competition between domestic and foreign firms. However, here competition is for the *domestic* market and *both* firms are subject to environmental regulation. Moreover, environmental regulation does not lower marginal costs of production (contrary to Greaker (2003) and Ambec and Barla (2002)), but rather raises them (the standard premise in environmental policy modeling). Hence, environmental policy does not proxy for an export subsidy in the sense of the strategic trade literature described above.[2]

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[2] This paper is also related to a growing literature on the interplay between environmental regulation and environmental R&D that is not concerned with the Porter Hypothesis per se and, hence, does not consider domestic vs. foreign/global distinctions (see Requate's (2005a) survey). Two strands of this literature are most relevant here. First, a subset of papers models R&D and price or output competition in oligopolistic environments. Montero (2002a, 2002b) studies how different policy instruments affect R&D incentives under different market structures (Cournot and Bertrand). A number of authors study optimal emission taxes under imperfect competition and find that the optimal tax is below its Pigovian level in order to correct excessively high output prices (see, for example, Katsoulacos and Xepapadeas,1996; Innes and Bial, 2002; Parry, 1995; Fees and Taistra, 2000). With regard to the Porter Hypothesis, this work is either

I. The Model

We consider a simple model in which a domestic firm (indexed by 1) and a foreign firm (indexed by 2) compete in differentiated products for the domestic market. Differentiated product demand is represented by a Hotelling address model wherein N consumers each demand one unit of product. This is the standard model of differentiated production competition in the literature (e.g., Norman and Thisse, 1999; Innes, 2006), with unit demands needed for tractability. For simplicity (and without loss), N is set equal to one. Each consumer's valuation of the domestic vs. foreign product depends upon the consumer's location in preference space. Specifically, each consumer is characterized by a parameter θ, with consumers (θ's) uniformly distributed on the unit interval. θ represents a consumer's distance from the domestic product, and $(1-\theta)$ the corresponding distance from the foreign product; transport (or preference) costs per unit distance are t. Absent transport/preference costs, consumers attach a value of V_1 to the domestic product and V_2 to the foreign product. Hence, given product prices (P_1, P_2), a θ-consumer buys the domestic (foreign) product when

$$V_1 - \theta t - P_1 \geq (<) V_2 - (1-\theta)t - P_2.$$

There is thus a critical θ_m that demarks consumers who buy from domestic ($\theta \leq \theta_m$) and foreign ($\theta > \theta_m$) firms:

(1) $$\theta_m = (1/2) + ([K+P_2-P_1]/2t) \quad , \quad \text{where} \quad K \equiv V_1 - V_2.$$

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agnostic (Montero, 2002) or at odds. Second, a small strand of the literature considers alternative government commitment strategies in the setting of environmental policies. Amacher and Malik (2002) and Denicolo (1999) compare effluent taxes and pollution permits selected either ex-ante (before R&D decisions are made) or ex-post (after R&D); in these papers, ex-ante policy commitments are not technology-contingent. Requate (2005b) allows the regulator to commit ex-ante to a menu of technology-contingent emission tax rates (or pollution permit quotas). Unlike the present paper, he does so in a model of competitive firms which can adopt (or not) a new environmental technology produced by a separate R&D monopolist and does not find that optimal ex-ante commitments support the Porter conjecture.

In this paper, we focus on cases in which the domestic firm may enjoy a preference advantage over the foreign firm:

Assumption 1: $K \geq 0$.

The two firms have constant unit costs of production. Unit costs depend upon the government's environmental (pollution abatement) standard, s, and the state of the firm's environmental technology, δ. A higher standard (higher s) represents tighter environmental regulation. Note that environmental regulation may take the form of product standards, such as tighter automotive emission requirements or biodegradable product content, or process standards that require less pollution in the production of each unit. In the case of product standards, foreign production (for the domestic market) can take place in the foreign (or domestic) country; in the case of process standards, however, we implicitly assume that foreign and domestic production takes place domestically. Whatever the nature of the standard (product or process), we assume that a common standard is applied to both firms; that is, consonant with exant trade agreements, a "national treatment" rule is in effect (Copeland, 2001). With a common technology, the two firms' unit costs are the same:

$$c_i = \text{firm i unit production costs} = c(s,\delta_i),$$

where $c_s>0$, $c_{ss}\geq 0$, $c_{sss}\geq 0$ (tighter standards raise costs), $c_\delta<0$, $c_{s\delta}<0$ (better technologies lower marginal and total costs of environmental compliance), and $c_{ss\delta}\geq 0$.

Beyond their effects on unit costs, environmental standards may also impose fixed setup costs on firms, F(s), where $F_s\geq 0$, $F_{ss} \geq 0$, and $F_{sss}\geq 0$ (costs rise with tighter standards). While plausible, the fixed costs imply that firm profits are affected by standards in the symmetric technology cases (when $\delta_1 = \delta_2$); in these cases, absent fixed costs, firm profits are invariant to standards.[3] Effects of standards on profits are important in what follows both because they can yield departures from globally optimal standards and, perhaps more importantly for our purposes, because the choice of standards can then affect firms' incentives for innovation in environmental technologies.

Environmental standards are motivated by external benefits of reduced pollution. Such benefits are assumed to be entirely domestic (so that there are no ignored cross-border spillovers). Because total consumption in the domestic market is fixed, these benefits can be measured simply by the function B(s), where $B_s>0$, $B_{ss}<0$ and $B_{sss}\leq 0$ (higher standards yield higher external benefits, but with diminishing returns).

A firm's technology is the outcome of its R&D efforts. For simplicity, we assume that there are two possible R&D outcomes: success (δ=1) and failure (δ=0). A higher firm investment in R&D, I_i, raises the probability of success, $q(I_i)$, where $q_I(I)>0$ and $q_{II}(I)<0$ (there are diminishing returns to R&D effort). Investment bears the unit cost r, so that firm i's R&D cost is rI_i. Given this structure, there are four possible technology states:

State A: Both firms succeed ($\delta_1 = \delta_2=1$).

State B: Domestic firm succeeds and foreign firm fails ($\delta_1 = 1, \delta_2=0$).

State C: Foreign firm succeeds and domestic firm fails ($\delta_1 = 0, \delta_2=1$).

State D: Both firms fail ($\delta_1 = \delta_2 = 0$).

The (domestic) government sets standards that are specific to each of these four technology states. We thus assume that technology outcomes are observable, and standards can be revised in response to these outcomes. We are principally concerned

[3] Profits would also depend upon standards in the symmetric technology states if consumer demands were elastic. We opt to capture such effects in a simpler (and plausible) way using fixed costs.

with how a domestic government that maximizes domestic welfare – ignoring effects on foreign firm profits – will choose these four standards. Several questions arise.

First, consider the government's *ex-post* choices of standards – when it maximizes domestic welfare, given technology outcomes. How do domestically optimal (ex-post) standards relate to their globally optimal counterparts? For example, are standards tighter (higher) than is globally optimal, a weak form of the Porter hypothesis? And how do standards respond to domestic innovation? For example, when the domestic firm succeeds and the foreign firm doesn't (state B), do standards tighten more than when the converse occurs (state C)?

Second, consider the *ex-ante* choices of standards – when the government can commit apriori to its ex-post regime of technology-specific standards, accounting for the effect of these commitments on firms' R&D decisions. Vis-à-vis ex-post optimal standards, are ex-ante optimal counterparts tighter in order to spur domestic R&D, the "pure" Porter hypothesis? In which technology states are the ex-ante standards tighter or weaker? And how does the desire to provide better R&D incentives affect departures from globally optimal standards?

A few comments are in order concerning how we go about addressing these questions. First, we assume that the domestic government cannot tax away foreign firm profit, but rather is restricted to the environmental policy tools of interest in this paper. Second, in principle, these policy tools could include both environmental taxes and environmental standards. We focus on standards alone primarily because environmental taxes are rarely used in practice (for political reasons and due to monitoring and enforcement costs) and such taxes might operate as an explicit mechanism to extract foreign firm profit. Third, we assume that the government cannot directly regulate R&D. R&D is notoriously difficult to measure and correspondingly easy to misrepresent, motivating a focus on policy tools that alter incentives for R&D, as in this paper and others (e.g., see Sappington, 1982; Innes and Bial, 2002). Fourth, there are two sources of ex-post market failure in this model: Imperfect competition and environmental externalities. In principle, the government could regulate both by combining environmental standards with output taxes/subsidies. In our model, however, a uniform per-unit output tax or subsidy, leveled on both domestic and foreign firms, has no effects of economic importance: all prices rise (fall) by the amount of the tax (subsidy), but firm profits and consumer demands (θ_m) remain the same. If the government can offer unit subsidies to the domestic firm only, then both sources of market failure can be addressed, but the government also has greater scope for disadvantaging the foreign competitor. In order to avoid such transparent discrimination against the foreign firm, we focus on a policy regime that only regulates the environment (with standards).

Fifth, we ignore cross-country effects of standards. Our positive analysis is quite easily extended to consider exogenous effects of technology change on firms' profits in foreign markets.[4] However, examining a full model of cross country spillovers – and the attendant strategic interplay between domestic and foreign governments in their standard-setting policies – is an important topic that we leave to future work.

Finally, although we will turn to the potential role for technology transfer in Section VI, we assume in the interim that such transfers do not take place, whether because they are unprofitable or too costly.

[4] See our expanded paper (available upon request), where we also discuss third party innovation and technology effects on fixed costs, neither of which alters our qualitative conclusions.

II. Ex-Post Market Equilibrium and Welfare

For a given state of technology, (δ_1,δ_2), and given standard s, the firms' costs are

(2) $c_1 = c(s, \delta_1)$, $c_2 = c(s, \delta_2)$ $\rightarrow$ Δ = cost difference = $c_1 - c_2$.

Given costs, firms choose prices to maximize their variable profits,

(3) Firm 1: $\max_{P_1} \theta_m()(P_1-c_1) - F(s)$, Firm 2: $\max_{P_2} (1-\theta_m())(P_2-c_2) - F(s)$

where $\theta_m()$ is given in equation (1). Solving these maximizations yields equilibrium prices, profits and market share θ_m:

(4a) $P_1 = c_1 + t + [(K-\Delta)/3]$, $P_2 = c_2 + t - [(K-\Delta)/3]$

(4b) $\pi_1(\Delta,s) = 2t\, \theta_m(\Delta)^2 - F(s)$, $\pi_2(\Delta,s) = 2t\, (1-\theta_m(\Delta))^2 - F(s)$, $\theta_m(\Delta) = .5+[(K-\Delta)/6t]$.

Throughout our analysis, we assume that effects of pro-domestic preferences (K>0) and regulation are not so strong as to entirely exclude either firm from the market:

Assumption 2. For relevant s, $\theta_m(\Delta)\varepsilon(0,1)$ in all technology states.

Domestic welfare is the sum of consumer surplus,

$$CS = (V_1-P_1)\, \theta_m + (V_2-P_2)\, (1-\theta_m),$$

firm 1 profit $\pi_1(\Delta,s)$, and external benefit B(s), less transport/preference costs T, and less firm 1 R&D investment cost, rI_1, where

$$T = t\{ .5 - \theta_m\, (1- \theta_m)\}.$$

Domestic welfare is thus:

(5) $W^D = \pi_1 + (V_1-P_1)\, \theta_m + (V_2-P_2)\, (1-\theta_m) - T - rI_1 + B(s)$

$= (.5t+V_2) + (K-\Delta)\, \theta_m(\Delta) - c_2 - \pi_2(\Delta,s) - rI_1 + t\, \theta_m(\Delta)\, (1- \theta_m(\Delta)) + B(s) - 2F(s)$,

where the first bracketed term is a constant that we can ignore (without loss). Global welfare adds back foreign firm profit:

(6) $W^G = W^D + \pi_2(\Delta,s) - rI_2$.

III. Ex-Post Optimal Regulation

In an ex-post domestic optimum, the chosen standard will maximize W^D in equation (5), given the technology, (δ_1,δ_2). The requisite first order condition for the maximization is (after simplification):

(7) $$\partial W^D/\partial s = (\partial B/\partial s) - (\partial F/\partial s) - \theta_m (\partial c_1/\partial s) - (1- \theta_m)(\partial c_2/\partial s) - (1/3)(\partial \Delta/\partial s)$$

$$= -(\partial \Delta/\partial s)(\theta_m(\Delta) + (1/3)) + (\partial B/\partial s) - (\partial F/\partial s) - (\partial c_2/\partial s) = 0.$$

Equation (7) has the following interpretation: The net domestic welfare benefit of increasing the environmental standard equals the environmental benefit (B_s), less the fixed cost to the domestic firm (F_s), less the impact on variable costs of production to the domestic and foreign firms (for fixed market share θ_m), and plus the domestic benefit of shifting market share to the domestic firm (the last term in (7)).

Similarly, the first order condition for an ex-post global optimum is:

(8) $$\partial W^G/\partial s = \partial W^D/\partial s + (2/3)(\partial \Delta/\partial s)(1-\theta_m(\Delta)) - (\partial F/\partial s)$$

$$= (\partial \Delta/\partial s)[(1-5\theta_m(\Delta))/3)] + (\partial B/\partial s) - 2(\partial F/\partial s) - \partial c_2/\partial s = 0.$$

Equation (8) subtracts the cost of higher standards in raising the fixed cost to the foreign firm (F_s) and the cost of the shift in market share to the foreign firm.

Assuming that requisite second-order conditions are satisfied (with sufficiently strong curvature in B(s)), equations (7)-(8) imply the following relationship between ex-post domestic and global optima:

(9) $(2/3)(\Delta_s)(1-\theta_m(\Delta)) - (\partial F/\partial s) < (>) 0 \quad \Leftrightarrow$

ex-post domestic optimal standard in technology state i = s_i^D

$> (<) s_i^G$ = ex-post global optimal standard in technology state i, where $\Delta_s = \partial\Delta/\partial s = 0$ in states A and D ($\delta_1=\delta_2$), $\Delta_s < 0$ in state B ($1=\delta_1>\delta_2=0$), and $\Delta_s > 0$ in state C ($0=\delta_1<\delta_2=1$). Hence, with $\theta_m(\Delta) <1$ (by Assumption 2) and $\partial F/\partial s\geq 0$, we have (with intuition to follow):

Proposition 1. (A) Provided firms have fixed costs of compliance with standards (F'>0), domestic optimal standards are higher than globally optimal counterparts, $s_i^D > s_i^G$, in technology states A, B, and D, and can be higher or lower in state C. (B) If there are no fixed costs of environmental compliance (F'=0), then domestic optimal standards are higher (lower) than global counterparts in state B (C), and the same in states A and D (c.f., Copeland, 2001).

Propositiion 1(B) mimics results of Copeland (2001). Proposition 1(A) indicates that ex-post optimal domestic standards are higher than global counterparts in the symmetric technology states A and D as well. To understand the intuition for these results, first consider case B, when the domestic firm has the technological advantage. Then elevating the environmental standard has the effect of raising the foreign firm's cost disadvantage, imparting an added competitive advantage (and hence, larger market share and profit) to the domestic firm. This "raising rival's cost" effect is a benefit to domestic welfare, but not to global welfare (where the domestic firm's profit gains are offset by foreign firm losses). In addition, a higher standard raises the foreign firm's fixed costs of compliance (with F'>0), a cost that is irrelevant to domestic welfare but relevant to global welfare. Both effects favor higher standards by a domestic (vs. global) planner. In cases A and D, when the firms have symmetric technologies, the second (fixed cost of standards) effect is present, but not the first (raising rival's costs); hence, so long as higher standards reduce profits of symmetric technology firms, the domestic planner will set a higher standard than is globally optimal. Finally, in case C – when the foreign firm has the technology advantage – the raising rival's cost effect runs in the opposite direction: lowering standards reduces the foreign firm's cost advantage to the benefit of the domestic firm. Hence, the two effects are offsetting and domestic optimal standards can be either higher or lower than global counterparts.

We interpret Proposition 1 as a weak form of the Porter hypothesis; so long as the domestic firm does not have an inferior environmental technology, standards that are higher than (globally) optimal are favored.

IV. Innovation and Ex-Ante Optimal Regulation

Anticipating the environmental standards in states A-D, each firm chooses its R&D investment, I_i, to maximize expected profits (assuming risk neutrality):

(10a) I_1: $\max_I \ \pi_1^*(I;I_2) \equiv \sum_z q_z(I,I_2)\,\pi_{1z} - rI \ \Rightarrow \ I_1 = I_1^{**}(s_A, s_B, s_C, s_D;I_2)$,

(10b) I_2: $\max_I \ \pi_2^*(I;I_1) \equiv \sum_z q_z(I_1,I)\,\pi_{2z} - rI \ \Rightarrow \ I_2 = I_2^{**}(s_A, s_B, s_C, s_D;I_1)$,

where $q_z(I_1,I_2)$ = probability of state z (e.g., $q_A(I_1,I_2)=q(I_1)q(I_2)$), π_{iz} = firm i profit in state z = $\pi_i(\Delta_z,s_z)$, Δ_z = firms' unit cost difference in state z = $c(s_z,\delta_{1z})-c(s_z,\delta_{2z})$, and s_z = anticipated environmental standard in state z. A Nash Equilibrium simultaneously solves problems (10a) and (10b),

$\{I_1^*(s_A, s_B, s_C, s_D), I_2^*(s_A, s_B, s_C, s_D)\}$: $I_1^{**}(s_A, \ldots,s_D;I_2)=I_1$ and $I_2^{**}(s_A, \ldots s_D;I_1)=I_2$.

In this section, we are interested in how the (domestic) government may want to devise its standards in view of their effects on firms' R&D investment incentives. So far, we have considered standards that are set to be ex-post optimal, maximizing domestic welfare in each technology state. However, in principle, the government may be able to commit to a regime of technology-specific standards. Such ex-ante commitments may deviate from their ex-post optimal counterparts because the government has an interest in motivating different technology investments than would otherwise be made. Specifically, in some states, the government may want to commit to tighter standards in order to spur more domestic investment in R&D; we interpret this as a form of the Porter conjecture. For example, Poreter and van der Linde (1995) stress that "properly designed environmental standards can trigger innovation."

As in related work (Requate, 2005,; Innes and Bial, 2002), we allow the government to commit ex-ante to a whole regime of environmental policies, each of which is specific to the technology state (A,B,C, and D).[5] Arguably in practice, government commitments to changes in standards are less nuanced. For example, a government may commit to a given tightening of a standard, regardless of technology outcomes (see Amacher and Malik, 2002; or Denicolo, 1999). However, in practice, regulators also generally leave "escape valves" to their commitments, allowing for a more lax standard when there is no innovation at all. Indeed, later in the paper when we consider the potential for technology transfer in the presence of plausible monotonicity constraints on standards, we find that optimal ex-ante commitments may take precisely this form, namely, a common commitment whenever there is a new technology (states A, B, and C) and a lower standard when there is no successful R&D (state D). In order to make meaningful comparisons between ex-post optimal standards (which are technology-specific) and ex-ante commitments, however, we allow the latter commitments to be technology-specific in what follows.

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[5] Unlike this other work, we focus on government setting of environmental *standards* in a model of differentiated product competition.

Our first objective is to determine how the government would like to change R&D investments at the margin, measured from the ex-post optimal benchpost. For example, given ex-post optimal standards, would domestic welfare rise if the domestic firm's R&D were increased marginally? If so, then the (welfare-maximizing) government has an interest in revising its regime of ex-post standards so as to spur more domestic R&D.

Expected domestic welfare can be written:

$$W^{D*} = \sum_{z} q_z(I_1,I_2)\, W_z^D - rI_1,$$

where $W_z^D(s_z)$ = ex-post domestic welfare in state z (per equation (5) above). Examining the marginal effects of domestic and foreign R&D on expected domestic welfare, evaluated at Nash Equilibrium levels of R&D investment, yields:

(11a) $\partial W^{D*}/\partial I_1 = q'(I_1)\{q(I_2)[(W_A^D - W_C^D)-(\pi_{1A}-\pi_{1C})]+(1-q(I_2))[(W_B^D - W_D^D)-(\pi_{1B}-\pi_{1D})]\}$,

(11b) $\partial W^{D*}/\partial I_2 = q'(I_2)\{q(I_1)[(W_A^D - W_B^D)-(\pi_{2A}-\pi_{2B})]+(1-q(I_1))[(W_C^D - W_D^D)-(\pi_{2C}-\pi_{2D})]\}$,

where we have substituted from first order conditions for problems (9a)-(9b). By showing that the bracketed differences on the right-hand-side of (11a) are positive at the ex-post optimum, and those on the right-hand-side of (11b) are negative, we obtain:

<u>Proposition 2</u>. Assume that standards are chosen to maximize ex-post domestic welfare, $\{s_A^D, s_B^D, s_C^D, s_D^D\}$. Then expected domestic welfare increases with marginal R&D by the domestic firm and, provided the following (sufficient) condition holds, decreases with marginal R&D by the foreign firm:

(12) $$s_B^D \geq (2/3)\, s_A^D.$$

Corollary 1. Condition (12) holds if either of the following (sufficient) conditions hold: $s_D^D \geq (s_A^D/3)$, or $B_s(0)–F_s(0)–c_s(0,0) \geq -(1/2)\Delta_s^*(s_A^D)$, where $\Delta_s^*=c_s(s,1)-c_s(s,0)$.

Successful domestic R&D yields two benefits to the domestic economy that are not captured by the domestic firm: (1) benefits of cost reductions that are passed onto consumers, and (2) external benefits of tighter standards brought about by the successful innovation. As a result, benefits of marginal domestic R&D are greater for the overall domestic economy than for the firm that chooses the R&D. In contrast, successful foreign R&D yields profit gains to the foreign firm that are excluded from domestic welfare, and yields losses in domestic firm profit that are irrelevant to the foreign firm's R&D calculus, but reduce the overall benefits of the R&D to the domestic economy. Both of these differences imply lower relative benefits of marginal foreign R&D to the domestic social planner than to the foreign firm that chooses the R&D, provided ignored external benefits are not too large.

Proposition 2 is the essential foundation of the Porter hypothesis as interpreted in this paper, and is our central analytical result. This proposition motivates departures from ex-post optimal standards in order to spur domestic R&D. Unfortunately, we cannot make general statements about how standards will be revised to achieve the ends suggested by Proposition 2. We turn now to why this is true.

The direct effects of revisions in standards on domestic R&D are easily derived (totally differentiating the first order conditions for problem (10a) and appealing to second order conditions):

(13a) $\partial I_1^{**}(.;I_2)/\partial s_A \overset{s}{=} d\pi_{1A}/ds_A \leq 0$ (<0 if $F_s(s_A)>0$),

(13b) $\partial I_1^{**}(.;I_2)/\partial s_B \overset{s}{=} d\pi_{1B}/ds_B$ (>0 if $d\pi_{1B}/ds_B > 0$), (13c) $\partial I_1^{**}(.;I_2)/\partial s_C \overset{s}{=} - d\pi_{1C}/ds_C > 0$,

(13d) $\partial I_1^{**}(.;I_2)/\partial s_D \overset{s}{=} d\pi_{1D}/ds_D \geq 0$ (>0 if $F_s(s_D)$>0).

These effects are suggestive of how the government may want to revise standards in order to spur domestic R&D: lowering s_A and (assuming domestic firm profit rises with the state B standard) raising s_B, s_C, and s_D. The intuition for these signs is straightforward. In the symmetric technology states, higher standards reduce profits by raising fixed costs of environmental compliance. Hence, a higher state A standard reduces the domestic firm's incentive to move from state C (when it fails in its R&D) to state A (when it succeeds). Conversely, a higher state D standard raises the firm's incentive to move from state D (when it fails) to state B (when it succeeds). As both of these moves are made more likely with higher R&D, the firm's R&D incentives fall with s_A and rise with s_D. Similar logic applies in the asymmetric technology states C and B. In state B (when firm 1 is the lone innovator), a higher standard raises domestic firm profit by elevating its cost advantage, but lowers profit by raising fixed compliance costs; provided the former effect dominates, an elevated standard raises the domestic firm's gain from moving to state B (when it succeeds) from state D (when it fails), thus raising R&D incentives. In state C (when the foreign firm is the lone innovator), a higher standard lowers domestic firm profit both by raising its cost disadvantage and by raising its fixed compliance costs; hence, a higher standard raises the firm's gain from moving to state A (when it succeeds) from state C (when it fails), again elevating R&D incentives.

Unfortunately, however, these qualitative prescriptions are only suggestive for two reasons. First, the indirect equilibrium effect of the changes in standards on I_1 – due to attendant changes in I_2 – can run in the opposite direction. For example, if marginal fixed costs (F_s) are sufficiently small, it can be shown that these indirect effects do run in the opposite direction, making general statements about comparative static effects difficult. Second, these qualitative changes in standards – lower in state A and higher in states B-D – are likely to spur greater domestic R&D, but are also likely to spur greater foreign R&D. Hence, by Proposition 6, these posited changes are likely to yield a tradeoff to a domestic planner, enhancing domestic welfare by prompting greater domestic R&D, but lowering domestic welfare by also prompting greater foreign R&D.

Unable to make general statements about how the domestic government will want to revise standards in order to spur domestic R&D, we turn to a numerical example to see if the suggestive prescriptions of equation (13) – and hence, the associated version of the Porter hypothesis (higher standards for states B-D) – can be supported.

V. A Numerical Example

As in Simpson and Bradford (1996), we construct a numerical example that is as simple as possible, and meant to illustrate possibilities as opposed to generalities or applications to specific empirical examples (something beyond the scope of this paper). Consider the following:

$c(s,\delta) = s(1-\alpha\delta)$, $\alpha\in(0,1)$,

$B(s) = b_0 s-(b_1/2)s^2$, $b_i>0$ for $i\in\{1,2\}$,

$F(s) = fs$, $f\geq 0$, $q(I) = 1 - e^{-I}$.

In this example, we calibrate parameters to ensure that, in the ex-post optimum, (1) both firms operate (earning non-negative profits in all cases), (2) firms enjoy positive marginal investment returns (at I=0), and (3) standards are positive. These constraints imply upper bounds on f and r (the unit cost of R&D investment I), restrictions on b_0 and b_1, and constraints on the relationship between K and t. [6]

This example gives rise to closed form ex-post optimal standards. [7] Given standards, we can calculate attendant ex-post profits and welfares. Given ex-post profits, equilibrium investment levels (when interior) solve the firms' R&D first order conditions,

$$\text{(14a)} \qquad I_1\text{: } (1-q_1)\ \{q_2(\pi_{1A}-\pi_{1C})+(1-q_2)(\pi_{1B}-\pi_{1D})\} - r = 0,$$

$$\text{(14b)} \qquad I_2\text{: } (1-q_2)\ \{q_1(\pi_{2A}-\pi_{2B})+(1-q_1)(\pi_{1C}-\pi_{2D})\} - r = 0,$$

where $(1-q_i) = q_i'$ for $q_i=1-e^{-I}$. In general, (14) can be solved for equilibrium success probabilities, $\{q_1, q_2\}$, and attendant investments, $I_i = -\ln(1-q_i)$. [8]

Turning to ex-ante optima – when the government commits to ex-post standards, considering their impact on firms' R&D decisions – we need to search over a range of possible standards to determine which menu achieves the highest possible level of expected domestic (or global) welfare in equilibrium. To do so, we conduct a fine grid search in a broad neighborhood of the ex-post optimum. [9]

We consider a rather wide range of alternative parameter settings.[10] As qualitative results are similar across the different settings, we illustrate outcomes by presenting two treatments: 1) a "base case" in which there is a moderate amount of

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[6] For example, we require that $b_1>(\alpha^2/6t)$ and $b_0>f+1$ to ensure positive ex-post optimal standards, and $s_C\alpha\leq K+3t$ and $K+s_B\alpha\leq 3t$ to ensure that $\theta_m\in(0,1)$.

[7] Specifically, for $z\in\{A,B,C,D\}$,

$$s_z^D = \{b_0-f-(1-\alpha\delta_2)-[\Delta_s(5t+K)/6t]\}/\{b_1-(\Delta_s^2/6t)\},$$

$$s_z^G = \{b_0-2f-(1-\alpha\delta_2)-(\Delta_s/3)[1.5+(5K/6t)]\}/\{b_1-(5\Delta_s^2/18t)\},$$

where $\Delta_s = \alpha(\delta_2-\delta_1)$.

[8] For the ex-post domestic optima, our parameter selections ensure interior R&D equilibria. When searching for an ex-ante optimum, however, some menus of standards can yield negative marginal investment returns for one or the other firm, implying an equilibrium q_i equal to zero.

[9] We vary each standard from a minimum equal to two-thirds of the lowest ex-post standard to four-thirds of the highest. For all of the many parameter settings that we consider, this search produced optima strictly interior to the search range. For each (and every) standard, we vary by increments of .0001.

[10] We consider $t\in\{2,3,4\}$, $K\in\{0,1,3\}<t$, $b_1\in\{1,2\}<b_0$, $b_0\in\{2,4\}$, $\alpha\in\{.4,.5,.6\}$, $f\in\{0,.1,.2\}$, and $r\in\{.07,.1\}$.

domestic preference (with K=1<t=3), and 2) an alternative case in which there is no domestic preference (K=0), more gain from technological innovation (α=.6 vs. α=.5), less cost of R&D (with r=.07 vs. r=.1) and lower costs of environmental compliance (with f=.1 vs. f=.2).[11]

Results from these two cases are described in Tables 1A and 1B, illustrating a number of key outcomes. First and foremost, when moving from an ex-post optimum to an ex-ante optimum (whether domestic or global), standards rise in states B, C, and D, and fall in state A. For the domestic social planner, the gain from these changes is due to the resulting increase in the domestic firm's R&D (see bottom panels of Tables 1A-1B). For the global planner, the gain is due to the resulting increase in both domestic and foreign R&D. These results illustrate the Porter hypothesis at work, and are obtained for all parameter settings that we consider.

Second, consistent with Proposition 1, ex-post optimal domestic standards are higher in states A, B, and D, and higher or lower in state C, vis-à-vis global counterparts (Proposition 1).

Third, in Case 2 (vs. Case 1), there are higher compliance-cost-reducing benefits of innovation (higher α) and lower costs of R&D (lower r); as a result, optimal standards are higher (whenever innovation occurs) and R&D investments are larger. Interestingly, however, R&D investments are larger for the foreign firm than for the domestic firm in the domestic Case 2 optimum. Because standards are more lax in state C than in state B,

[11] Case 1 parameters are t=3, K=1, b_1=1, b_0=2, α=.5, f=.2, and r=.1. Case 2 parameters are t=2, K=0, b_1=1, b_0=2, α=.6, f=.1, and r=.07.

firm 2 benefits more from avoiding state B than firm 1 benefits from avoiding state C. Hence, firm 2 can have the greater incentive to invest in R&D. [12]

Fourth and finally, a modest point illustrated by Case 1. From the bottom right-hand column of Table 1A, average global welfare is higher in the ex-post domestic optimum (W^{G*}=1.491) than in the ex-post global optimum (W^{G*}=1.488). Recall that, given ex-post regulation, standards are higher in the domestic optimum than in the global optimum. This may lead to more environmental R&D with domestically (vs. globally) optimal regulation, which may even lead to a higher level of average global welfare (as in Case 1). Hence, if ex-ante commitments to menus of standards are not possible, it need not be desirable (from the standpoint of global welfare) for international bodies to meddle in the regulatory affairs of the domestic government in an effort to achieve ex-post global optima.

VI. Technology Transfer

So far, we have assumed that the government can freely choose standards in the four technology states and that there is no technology transfer between firms. As illustrated in the numerical example, the first assumption can lead to optimal standards that are higher when only one firm successfully innovates (states B and C) than when both firms succeed (state A). Arguably, such a response to innovation – even though motivated by a desire to spur R&D – is implausible; indeed, it provides firms with an incentive to claim success even though they have in fact failed in their R&D. Avoiding

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[12] The careful reader may be puzzled by negative values of ex-post domestic welfare (W_z^D) in Case 2. However, these values do not include the fixed component of domestic welfare, V_2-(t/2). We assume in this paper that the fixed benefits of consumption, $\{V_1, V_2\}$, are sufficiently large that the market is always fully served. With such values, the full measure of ex-post domestic welfare ($W_z^D + V_2$-(t/2)) is always positive in Case 2 (and all other cases examined).

such an incentive requires the plausible restriction that standards do not fall with more innovation; that is, $s_A \geq \max(s_B, s_C)$. We now impose this constraint.

With regard to technology transfer, we implicitly assume in the foregoing analysis that transfer costs are large. Let us now suppose instead that technology transfer is costless and occurs whenever the two firms can obtain collective profit gains by so doing. Then we can show:

<u>Proposition 3</u>. (A) If $s_A \geq s_B$ or if marginal fixed costs (F_s) are sufficiently small for $s \in [s_A, s_B)$, then technology transfer does not occur in state B (when only the domestic firm succeeds in its R&D). (B) Suppose that $\theta_m \leq (1/2)$ in state A, and either $s_A \geq s_C$ or marginal fixed costs are sufficiently small for $s \in [s_A, s_C)$. Then technology transfer does not occur in state C. (C) Suppose that $\theta_m \geq (1/2)$ in state C, and either $s_C \geq s_A$ or marginal fixed costs are sufficiently small for $s \in [s_C, s_A)$. Then technology transfer, if costless, occurs in state C.

<u>Corollary 2</u>. If K=0 and $s_A \geq s_z$ for $z \in \{B,C\}$, then technology transfer does not occur.

Under certain circumstances, Proposition 3 indicates that the two firms collectively enjoy higher profit when they have asymmetric technologies (as in states B and C) than when both succeed in their R&D (state A). Clearly, under these circumstances, technology transfer cannot occur absent government intervention. For example, Corollary 2 implies that unsubsidized technology transfer cannot occur in Case 2 of our numerical example, given our assumed monotonicity constraint on standards. However, such circumstances need not always hold. For example, it is easily seen (from Table 1) that technology transfer will not occur in the ex-post optima of either Cases 1 or

2 (with π_1+π_2 higher in states B and C than in state A). However, if costless, technology transfer can occur in the ex-ante optimum for Case 1.

i. Private Technology Transfer with Monotonicity Constrained Standards. If technology transfer can occur, government regulators may want to adjust standards in order to spur both innovation and technology exchange. To account for this prospect, we will suppose that joint profit gains from technology transfer are obtained entirely by the technology seller, who is implicitly assumed to make a take-it-or-leave-it technology sale offer to the rival firm. Although alternative rent-splitting rules are possible (and perhaps more plausible), we assume that the seller receives all gains from trade in order to ensure that there are no "spillover" benefits of R&D that might otherwise motivate tight environmental policy.[13]

Constraining standards to be monotonic in technology and allowing technology transfer yields the ex-ante optima described in Table 2.[14] Particularly notable about the Case 1 domestic optimum here is that it supports a very strong form of the Porter hypothesis: in every technology state, standards are higher than in the ex-post optimum. In both the domestic and global Case 1 optima, note that technology transfer occurs in

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[13] We also perform our numerical optimization under a premise that gains from technology trade are shared equally by the two firms; with this rule, results are qualitatively similar to those reported above (details available from the author upon request). To understand the "splitting" rules, note that the net profit gain to technology transfer in state B is: $G_B = (\pi_{1A}+\pi_{2A})-(\pi_{1B}+\pi_{2B})$. If G_B>0, then technology transfer yields the following state B profits to firms 1 and 2 under an "equal splitting" rule: $\pi^*_{1B}=\pi_{1B}+(G_B/2)$, $\pi^*_{2B}=\pi_{2B}+(G_B/2)$. However, when the seller obtains all gains, technology transfer yields: $\pi^*_{1B}=\pi_{1B}+G_B$, $\pi^*_{2B}=\pi_{2B}$.

[14] Note that in Case 2 (where K=0), the monotonicity constraint ($s_A\geq s_i$, $i\in\{B,C,D\}$) ensures that technology transfer does not occur. Absent any constraints on standards, we find in our Case 1 numerical example that the government manipulates its standards not only to elicit technology exchange whenever R&D outcomes are asymmetric, but also to capriciously advantage the domestic firm; this it does by raising the state B standard to almost three times the level of its state A standard. Because the state B standard is never actually implemented (due to technology transfer), it can be set particularly high without cost to domestic welfare. However, such a perverse distortion of standards is clearly implausible.

state C – when societal gains from transfer are particularly large – but not in state B where the domestic firm retains its technological advantage.

ii. Subsidized Technology Transfer with Monotonicity Constrained Standards. So far, we have assumed that there is no government intervention to promote technology exchange. In the domestic Case 1 optimum described in Table 2, for example, the domestic government would benefit from gratuitous technology exchange in state B of the ex-ante optimum, gaining the net welfare, $W_A^D - W_B^D = .061$. However, achieving such an exchange requires government intervention (as joint profits are lower in state A) and a transfer process that may yield different firm profits than would otherwise occur in state A. Specifically, let us suppose that the government offers the technology winner a subsidy for technology transfer just large enough to make the transfer profitable; this minimum subsidy equals the net profit loss to the two firms from the exchange,

(16) Mimimum transfer subsidy = TS = $(\pi_{1B}+\pi_{2B})-(\pi_{1A}+\pi_{2A}) = .064$

With the subsidy of eq. (16), the firms will exchange the technology at a price that exactly preserves their pre-transfer profits, and domestic welfare in state B becomes:

$$W_B^{DT} = \text{post-transfer domestic welfare in state B} = (W_A^D + \pi_{2A}) - \pi_{2B} - TS$$

$$= 1.078 > .895 = W_B^D = \text{pre-transfer domestic welfare in state B.}$$

Hence, despite its cost, the technology transfer subsidy yields a higher level of domestic welfare.

Given the scope for transfer subsidies to increase domestic welfare, let us consider the government's regulatory choice problem when (1) technology transfer is costless (as before), (2) if profitable, private technology exchange occurs without any government subsidy or tax, with all net gains obtained by the selling firm (as before), (3) if it would not otherwise occur and raises domestic welfare, technology exchange is subsidized by the government at the minimum level that elicits transfer, and (4) standards are constrained not to fall with technological improvement. Table 3 describes the resulting ex-ante domestic optima for Cases 1 and 2. Note that, in both cases, the government subsidizes technology transfer when it would otherwise not occur, and technology exchange is thereby elicited whenever only one firm wins the R&D race. Also in both cases, the monotonicity constraint on standards binds in both states B and C; hence, whenever any innovation occurs, regardless of by whom, standards rise to the same elevated level. In case 1, this translates to a strong form of the Porter hypothesis, with ex-ante optimal standards higher than ex-post optimal counterparts in all technology states. Case 2 exhibits almost as strong a form of the Porter hypothesis, with the state A standard only slightly lower than its ex-post optimal counterpart and all other standards substantially higher. Finally, note that the increased scope for technology transfer – with subsidies eliciting transfer in state B as well as state C – leads to higher optimal standards in states A-C (comparing Tables 2 and 3). A subsidized state B transfer eliminates the ex-post welfare cost of elevating s_B in order to spur R&D. Given the binding monotonicity constraint, the heightened incentive to raise s_B also motivates a higher s_A, which in turn permits an innovation-spurring increase in s_C.

VII. Conclusion

This paper studies environmental regulation in an institutional setting that, in a number of respects, reflects realities for many regulated sectors and seems broadly consistent with initial expressions of the "Porter Hypothesis" (e.g., Porter, 1991). Specifically, we assume that pollution abatement standards are the instruments of environmental policy; imperfectly competitive domestic and foreign firms compete in differentiated products for the domestic market; and the firms engage in environmental R&D that can reduce their costs of environmental compliance. In this setting, we investigate whether and how the "Porter Hypothesis" is supported is two specific senses. First, does the domestic government, when selecting standards after R&D outcomes have been realized (ex-post), choose tighter environmental regulations than would a global social planner? And second, when the government is able to commit ex-ante to a technology-specific menu of environmental regulations, considering their impact on the firms' R&D investments, are the optimally chosen standards tighter than their ex-post optimal counterparts? We find that the answers to both questions are often "yes," despite the absence of any explicit market failures, or any marginal-production-cost-reducing benefits of environmental compliance, that prior work cites as motive for "tight" emission regulation (e.g., Ambec and Barla, 2002; Mohr, 2002; Hart, 2004; Greaker, 2003).

The logic for these conclusions is straightforward. First, a domestic government (i) benefits from giving its domestic firm a competitive advantage, and (ii) does not consider costs of its regulations on foreign producers. Vis-à-vis a global social planner, the domestic government thus sets a higher environmental standard when the domestic industry has a relatively superior pollution abatement technology; by so doing, it advantages the domestic firm by implicitly raising the foreign rival's costs (c.f., Salop and Scheffman, 1987). When the firms' environmental technologies are symmetric, tighter standards are also favored because regulatory costs to the foreign firm are ignored. Second, in making its R&D decisions, the domestic firm ignores two societal benefits of an improved environmental technology: the external benefits of enhanced environmental performance and cost-saving benefits that are passed onto consumers. As a result, a social planner would like to spur greater domestic R&D by committing to an appropriately revised regime of standards. Tighter pollution standards often serve this end. For example, tightening the standard enacted when only the domestic firm succeeds in its environmental R&D, raises the firm's profit from success and thereby encourages more R&D. Likewise, raising the standard enacted when either no new technology is discovered or only the foreign firm succeeds in its R&D (not the domestic firm) raises the domestic firm's penalty from failure in its environmental R&D; again, the domestic firm then has an incentive to invest more in environmental research.

Two criticisms of these conclusions should be noted. First, they are not perfectly general. And second, they apply potentially to government regimes of environmental standards, but have not been established for other regulatory instruments (such as effluent taxes). While both of these criticisms argue for further research, we close with two reasons to think that our "Porter Hypothesis" conclusions may be potentially broadly relevant. The first, of course, is that standards are in fact the regulatory instrument of choice in the vast majority of actual environmental policy regimes enacted in practice. And second, in our numerical example, we obtain "Porter Hypothesis" outcomes for all of the broad range of parameter settings considered. While the example is clearly illustrative, the broad consistency of our results suggests that Porter's conclusions may not be the proverbial exception to the rule.

Appendix

Proof of Proposition 2. Let:

W_z^D = domestic welfare in state z with ex-post optimal standard s_z^D

$= (K-\Delta_z)\theta_z - c_{2z} + t\theta_z(1-\theta_z) - 2t(1-\theta_z)^2 + B(s_z^D) - F(s_z^D)$,

where $\Delta_z = c(s_z^D,\delta_{1z}) - c(s_z^D,\delta_{2z})$, $c_{2z} = c(s_z^D,\delta_{2z})$, $\theta_z = \theta(\Delta_z) = (1/2)+[(K-\Delta_z)/6t]$, and we ignore the constant $V_2-(t/2)$;

π_z^D = domestic firm profit in state z with $s_z^D = 2t\theta_z^2 - F(s_z^D)$;

π_z^F = foreign firm profit in state z with $s_z^D = 2t(1-\theta_z)^2 - F(s_z^D)$.

Domestic R&D. It suffices to show (comparing domestic firm profit and welfare maximization first order conditions for domestic R&D):

$W_B^o \equiv W_B^D - \pi_B^D > W_D^D - \pi_D^D \equiv W_D^o$ and $W_A^o \equiv W_A^D - \pi_A^D > W_C^D - \pi_C^D \equiv W_C^o$.

Now define, for $\delta=\delta_1$,

$c^*(s,\delta) = c(s,0) + \delta\,(c(s,1)-c(s,0))$,

$s_A^*(\delta) = s_C^D + \delta\,(s_A^D - s_C^D)$,

$s_B^*(\delta) = s_D^D + \delta\,(s_B^D - s_D^D)$,

$F_z^*(s,\delta) = \{F(s_z^*(\delta)) - g_z(s_z^*(\delta), \delta)\, s_z^*(\delta)\} + g_z(s_z^*(\delta), \delta)\, s, \quad z\in\{A,B\}$,

$W_z^{D*}(s, \delta) = (K-\Delta_z)\theta(\Delta_z) - c(s,0) + t\theta(\Delta_z)(1-\theta(\Delta_z)) - 2t(1-\theta(\Delta_z))^2 + B(s), \quad z\in\{A,B\}$,

$W_z^{D**}(\delta) = W_z^{D*}(s_z^*(\delta),\delta) - F_z^*(s_z^*(\delta),\delta), \quad z\in\{A,B\}$,

$\pi_z^{D*}(\delta) = 2t(\theta(\Delta_z^*))^2 - F(s_z^*(\delta)), \quad z\in\{A,B\}$,

where $\Delta_A=c^*(s,\delta)-c(s,1)$, $\Delta_B=c^*(s,\delta)-c(s,0)$, $\Delta_A^*=c^*(s_A^*(\delta),\delta) - c(s_A^*(\delta),1)$,

$\Delta_B^*=c^*(s_B^*(\delta),\delta) - c(s_B^*(\delta),0)$, and $g_z(s, \delta)=\partial W_z^{D*}(s,\delta)/\partial s$.

Now note:

(A1a) $\quad W_z^{D**}(1) - \pi_z^{D*}(1) = W_z^o \quad , \quad z \in \{A,B\},$

(A1b) $\quad W_A^{D**}(0) - \pi_A^{D*}(0) = W_C^o \quad , \quad W_B^{D**}(0) - \pi_B^{D*}(0) = W_D^o.$

(A2) $\quad d\,W_z^{D**}(\delta)/d\delta = \{(\partial W_z^{D*}(s_z^*(\delta),\delta)/\partial s) - (\partial F_z^*(s_z^*(\delta),\delta)/\partial s)\}(ds_z^*(\delta)/d\delta)$

$+ \{(\partial W_z^{D*}(s_z^*(\delta),\delta)/\partial\delta) - (\partial F_z^*(s_z^*(\delta),\delta)/\partial\delta)\}$

$= \{(\partial W_z^{D*}(s_z^*(\delta),\delta)/\partial\delta) - (\partial F_z^*(s_z^*(\delta),\delta)/\partial\delta)\} \quad , \quad z \in \{A,B\}$

We want to show that:

(A3a) $\quad W_B^o - W_D^o = \int_0^1 \{(dW_B^{D**}(\delta)/d\delta) - (d\pi_B^{D*}(\delta)/d\delta)\}\, d\delta > 0,$

(A3b) $\quad W_A^o - W_C^o = \int_0^1 \{(dW_A^{D**}(\delta)/d\delta) - (d\pi_A^{D*}(\delta)/d\delta)\}\, d\delta > 0,$

where the equalities follow from (A1). Expanding the right hand sides (using (A2)):

$$dW_z^{D**}(\delta)/d\delta = -(\partial\Delta_z/\partial\delta)(\theta+(1/3)) - F'(s_z^*(\delta))(ds_z^*(\delta)/d\delta)$$

$$d\pi_z^{D*}(\delta)/d\delta = (-2\theta/3)[(\partial\Delta_z/\partial\delta) + (\partial\Delta_z/\partial s)(ds_z^*(\delta)/d\delta)] - F'(s_z^*(\delta))(ds_z^*(\delta)/d\delta),$$

where $\partial\Delta_z/\partial\delta = c(s,1)-c(s,0) \equiv \Delta^*(s)$, and we have

$$\partial\Delta_B/\partial s = \delta(d\Delta^*(s)/ds) \leq 0 \quad , \quad \partial\Delta_A/\partial s = (\delta-1)(d\Delta^*(s)/ds) \geq 0.$$

Hence,

(A4) $\quad (dW_z^{D**}(\delta)/d\delta) - (d\pi_z^{D*}(\delta)/d\delta) = \{-\Delta^*(s_z^*(\delta))(1+\theta) + 2\theta(\partial\Delta_z()/\partial s)(ds_z^*(\delta)/d\delta)\}/3.$

Now, for z=A, the right hand side of (A4) is positive (with $\Delta^*<0$, $\partial\Delta_A()/\partial s \geq 0$, and $ds_A^*(\delta)/d\delta = s_A^D - s_C^D > 0$), establishing that $W_A^o - W_C^o > 0$ (equation (A3b)). For z=B,

$$(dW_B^{D**}(\delta)/d\delta) - (d\pi_B^{D*}(\delta)/d\delta) = \{-\Delta^*(1+\theta) + 2\theta\delta\Delta_s^*(s_B^D - s_D^D)\}/3$$

$> (2\theta/3)\{-\Delta^* + \delta\, \Delta^*_s\, (s^D_B - s^D_D)\} \overset{s}{=} -\Delta^*(s^*_B(\delta)) + \delta\, \Delta^*_s(s^*_B(\delta))(s^D_B - s^D_D)\} \equiv X(\delta),$

where the inequality is due to $\Delta^*<0$ and $\theta<1$. Differentiating the right hand side:

$$dX/d\delta = \delta\, (s^D_B - s^D_D)^2 \Delta^*_{ss}\, (s^*_B(\delta)) \geq 0,$$

where the inequality is due to $\Delta^*_{ss}() = c_{ss}(s,1)-c_{ss}(s,0) \geq 0$. Hence, because $X(0)>0$, we have $X(\delta)>0$ for all $\delta\in[0,1]$, thus establishing that $W^o_B - W^o_D > 0$ (equation (A3a)).

Foreign R&D. It suffices to show:

$$W^o_C \equiv W^D_C - \pi^F_C < W^D_D - \pi^F_D \equiv W^o_D \quad \text{and} \qquad W^o_A \equiv W^D_A - \pi^F_A < W^D_B - \pi^F_B \equiv W^o_B .$$

Now define, for $\delta=\delta_2$,

$$s^*_A(\delta) = s^D_B + \delta\, (s^D_A - s^D_B),$$

$$s^*_C(\delta) = s^D_D + \delta\, (s^D_C - s^D_D),$$

$c^*(s,\delta)$, $F^*_z(s,\delta)$, $W^{D*}_z(s, \delta)$, and $W^{D**}_z(\delta)$ as above, with $z\in\{A,C\}$,

$$\pi^{F*}_z(\delta) = 2t(1-\theta(\Delta^*_z))^2 - F(s^*_z(\delta)), \quad z\in\{A,C\},$$

where now $\Delta_A=c(s,1)-c^*(s,\delta)$, $\Delta_C=c(s,0)-c^*(s,\delta)$, $\Delta^*_A=c(s^*_A(\delta),1) - c^*(s^*_A(\delta), \delta)$, $\Delta^*_C=c(s^*_C(\delta),0) - c^*(s^*_C(\delta), \delta)$, and $g_z(s, \delta)=\partial W^{D*}_z(s,\delta)/\partial s$ as before.

Now note:

(A1a') $\qquad W^{D**}_z(1) - \pi^{F*}_z(1) = W^o_z \quad , \quad z\in\{A,C\},$

(A1b') $\qquad W^{D**}_A(0) - \pi^{F*}_A(0) = W^o_B \quad , \quad W^{D**}_C(0) - \pi^{F*}_C(0) = W^o_D.$

(A2') $\qquad d\, W^{D**}_z(\delta)/d\delta = \{(\partial W^{D*}_z(s^*_z(\delta),\delta)/\partial\delta)-(\partial F^*_z(s^*_z(\delta),\delta)/\partial\delta)\} \quad , \quad z\in\{A,C\}.$

We want to show that:

(A3a') $W^{o}_{C} - W^{o}_{D} = \int_0^1 \{(dW^{D**}_{C}(\delta)/d\delta)-(d\pi^{F*}_{C}(\delta)/d\delta)\}\, d\delta < 0,$

(A3b') $W^{o}_{A} - W^{o}_{B} = \int_0^1 \{(dW^{D**}_{A}(\delta)/d\delta)-(d\pi^{F*}_{A}(\delta)/d\delta)\}\, d\delta < 0,$

Expanding the right hand sides:

$$dW^{D**}_{z}(\delta)/d\delta = \Delta^*(s^*_z(\delta))(\theta-(2/3)) - F'(s^*_z(\delta))(ds^*_z(\delta)/d\delta)$$

$$d\pi^{F*}_{z}(\delta)/d\delta = (2/3)(1-\theta)[-\Delta^*(s^*_z(\delta)) + (\partial\Delta_z/\partial s)(ds^*_z(\delta)/d\delta)] - F'(s^*_z(\delta))(ds^*_z(\delta)/d\delta),$$

where $\partial\Delta_A/\partial s = (1-\delta)\Delta^*_s(s^*_z(\delta)) \leq 0$ and $\partial\Delta_C/\partial s = -\delta\Delta^*_s(s^*_z(\delta)) \geq 0$. Hence,

(A4') $\{(dW^{D**}_{z}(\delta)/d\delta)-(d\pi^{F*}_{z}(\delta)/d\delta) = \{\Delta^*(s^*_z(\delta))\theta - 2(1-\theta)(\partial\Delta_z()/\partial s)(ds^*_z(\delta)/d\delta)\}/3.$

Now, for z=C, the right hand side of (A4') is negative (with $\Delta^*<0$, $\theta>0$, $\theta<1$, $\partial\Delta_C()/\partial s\geq 0$, and $ds^*_C(\delta)/d\delta = s^D_C - s^D_D > 0$, given K<t by assumption), establishing that $W^o_C - W^o_D < 0$ (equation (A3b')). For z=A, the right hand side is negative when $s^D_A \leq s^D_B$ (with $\partial\Delta_A()/\partial s \leq 0$ and $ds^*_A(\delta)/d\delta = s^D_A - s^D_B \leq 0$ in this case). The remaining case is z=A with $s^D_A > s^D_B$; for this case, with $\theta \geq (1/2)$ (by $K \geq 0$ and $\delta_1 = 1 \geq \delta = \delta_2$, and hence, $\Delta_A \leq 0$) and $(\partial\Delta_A/\partial s)(ds^*_z/d\delta) \leq 0$,

$$(dW^{D**}_{B}(\delta)/d\delta)-(d\pi^{D*}_{B}(\delta)/d\delta) \leq \{\Delta^* - 2(1-\delta)\Delta^*_s\,(s^D_A - s^D_B)\}(1/6) \equiv (1/6)\,X(\delta),$$

where

$$dX/d\delta = 3\Delta^*_s(\,s^D_A - s^D_B\,)\} - 2(1-\delta)\,(s^D_A - s^D_B)^2\Delta^*_{ss} < 0,$$

with the inequality due to $\Delta^*_s<0$ and $\Delta^*_{ss} \geq 0$ (by $c_{ss\delta}\geq 0$). Hence, if $X(0)\leq 0$, then $X(\delta)<0$ for all $\delta\in[0,1]$ and, therefore, $W^o_A - W^o_B<0$. Now note that, with.$\Delta^*(0)\leq 0$, $\Delta^*_s<0$ and $\Delta^*_{ss}\geq 0$, $\Delta^*(s^D_B)\leq \Delta^*_s(s^D_B)\, s^D_B$. Hence,

$$X(0) = \Delta^*(s^D_B) - 2\Delta^*_s(s^D_B)(s^D_A - s^D_B) \leq \Delta^*_s(s^D_B)(3s^D_B - 2s^D_A) \leq 0,$$

where the inequality follows from $\Delta^*_s<0$ and $(2/3)s^D_A\leq s^D_B$ (by premise). QED.

Proof of Corollary 1. If $s^D_D\geq (s^D_A/3)$, then

$$s^D_B \geq (1/2)(s^D_A + s^D_D) \quad \Rightarrow \quad s^D_B \geq (2/3)\, s^D_A.$$

Hence, we need to show that $s^D_B \geq (1/2)(s^D_A + s^D_D)$. Note that the first order condition for choice of s^D_B can be written:

$$\partial W^D_B/\partial s = B_s - F_s - c_s(s,0)((2/3)-\theta) - c_s(s,1)(\theta+(1/3)).$$

Because the right hand side is increasing in θ, and θ>(1/2) in state B,

$$\partial W^D_B/\partial s > B_s - F_s - c_s(s,0)(1/6) - c_s(s,1)(5/6) \equiv J(s).$$

With $B'''\leq 0$, $F'''\geq 0$, anc $c_{sss}\geq 0$, J(s) is weakly concave. Hence,

$$J((1/2)(s^D_A + s^D_D)) \geq (1/2)\,[J(s^D_D)+J(s^D_A)] = -(2/3)\,\Delta^*_s(s^D_D) + (1/6)\int_{sd}^{sa} \Delta^*_{ss}(s)\,ds > 0,$$

where sa= s^D_A and sd=s^D_D, the equality substitutes from the first order conditions defining s^D_D (where $B_s-F_s=c_s(s,0)$) and s^D_A (where $B_s-F_s=c_s(s,1)$), and the final inequality is due to $\Delta^*_{ss}\geq 0$, $s^D_A > s^D_D$, and $\Delta^*_s<0$. We thus have $\partial W^D_B/\partial s>0$ at $s=(1/2)(s^D_A + s^D_D)$, and hence, $s^D_B \geq (1/2)(s^D_A + s^D_D)$.

Finally we need to show that $s_D^D \geq (s_A^D/3)$ if the Corollary's second condition holds. Let

$J(s) \equiv \partial W_D^D/\partial s > B_s\text{-}F_s\text{-}c_s(s,0)$.

By concavity of J,

$J(s_A^D/3) \geq (1/3)\Delta_s^*(s_A^D) + (2/3)(B_s(0)\text{-}F_s(0)\text{-}c_s(s,0))$.

Hence, if the Corollary's second condition holds, $\partial W_D^D/\partial s \geq 0$ at $s = s_A^D/3$. QED.

<u>*Proof of Proposition 3*</u>. Define

$\Pi(\Delta_z)$ = joint domestic and foreign firm profit before fixed costs

$= 2t\{ \theta_m(\Delta_z)^2 + (1\text{-}\theta_m(\Delta_z))^2 \}$,

where $\Delta_z = c(s,\delta_{1z})\text{-}c(s,\delta_{2z})$ = cost difference in state z.

(A) It suffices to show:

(A5) $$\Pi(\Delta_B) - 2F(s_B) \geq \Pi(\Delta_A) - 2F(s_A),$$

so that technology transfer is not profitable. Given our premises ($s_A \geq s_B$ or F_s sufficiently small), (A5) will hold provided $\Pi(\Delta_B) > \Pi(\Delta_A)$. Now note:

(A6) $$\partial\Pi/\partial\Delta \overset{s}{=} (2/3)(1\text{-}2\theta_m) < (>)\ 0 \quad \text{as} \quad \theta_m > (<)\ (1/2).$$

With $\Delta_A=0$, $\theta_m(\Delta_A=0) \geq (1/2)$ (with $K \geq 0$), $\Delta_B<0$, and $\theta_m(\Delta)>(1/2)$ for $\Delta<0$, $\Pi(\Delta_B) > \Pi(\Delta_A)$.

(B) By similar reasoning, it suffices to show that $\Pi(\Delta_C) > \Pi(\Delta_A)$ under the indicated conditions. With $\Delta_A=0$, $\theta_m(\Delta_A=0) \leq (1/2)$ by assumption, $\Delta_C>0$, and $\theta_m(\Delta_C)<(1/2)$ (by $\theta_m(0) \leq (1/2)$ and $\partial\theta_m/\partial\Delta<0$), (A6) implies the desired inequality.

(C) It suffices to show that $\Pi(\Delta_C) < \Pi(\Delta_A)$. With $\Delta_C>0$, $\theta_m(\Delta_C)\geq (1/2)$, $\Delta_A=0$, and $\theta_m(\Delta_A)>(1/2)$ (by $\theta_m(\Delta_C)\geq (1/2)$, $\partial\theta_m/\partial\Delta<0$, and $\Delta_C>\Delta_A=0$), (A6) implies the desired inequality. QED.

Proof of Corollary 2. When K=0, $\theta_m(\Delta_A)=(1/2)$. Hence, with $s_A\geq s_z$, $z \in \{B,C\}$, the prior requirements of Proposition 3(A)-(B) are satisfied. QED.

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Table 1A. Numerical Results for Case 1

	State z	s_z	θ_z	π_{1z}	π_{2z}	W_z^D	W_z^G
1) Ex-Post Domestic Optimum	A	1.300	.555	1.592	0.925	.956	1.881
	B	1.262	.591	1.840	0.753	.896	1.649
	C	0.868	.531	1.521	1.144	.482	1.626
	D	0.800	.555	1.692	1.025	.431	1.456
2) Ex-Ante Domestic Optimum	A	1.083	.555	1.635	0.968	.933	1.901
	B	1.355	.593	1.840	0.722	.892	1.614
	C	1.311	.519	1.355	1.125	.385	1.510
	D	1.093	.555	1.633	0.966	.388	1.355
3) Ex-Post Global Optimum	A	1.100	.555	1.632	0.965	.936	1.901
	B	0.917	.581	1.842	0.870	.838	1.707
	C	0.823	.533	1.538	1.146	.481	1.627
	D	0.600	.555	1.732	1.065	.411	1.476
4) Ex-Ante Global Optimum	A	0.787	.555	1.694	1.028	.825	1.852
	B	1.005	.583	1.842	0.840	.864	1.704
	C	1.000	.528	1.471	1.138	.474	1.612
	D	0.767	.555	1.698	1.032	.431	1.462

	q_1	q_2	π_1^*	π_2^*	$\partial W^{D*}/\partial I_1$	$\partial W^{D*}/\partial I_2$	$\partial W^{G*}/\partial I_1$	$\partial W^{G*}/\partial I_2$	W^{D*}	W^{G*}
1) Ex-Post Dom. Opt.	.232	.236	1.655	0.966	.259	-.059	.060	.041	.525	1.491
2) Ex-Ante Dom. Opt	.593	.526	1.543	0.858	.114	-.089	.034	.011	.609	1.467
3) Ex-Post Global Opt.	.093	.000	1.732	1.047	.287	-.027	.110	.055	.441	1.488
4) Ex-Ante Global Opt.	.395	.278	1.650	0.962	.148	-.092	.046	.008	.554	1.516

Table 1B. Numerical Results for Case 2

	State z	s_z	θ_z	π_{1z}	π_{2z}	W_z^D	W_z^G
1) Ex-Post Domestic Optimum	A	1.500	.500	0.850	0.850	.625	1.475
	B	1.443	.572	1.165	0.588	.510	1.098
	C	1.031	.448	0.701	1.114	.015	1.129
	D	.900	.500	0.910	0.910	-.095	0.815
2) Ex-Ante Domestic Optimum	A	1.441	.500	0.856	0.856	.623	1.479
	B	1.594	.580	1.185	0.547	.499	1.046
	C	1.452	.427	0.585	1.166	-.070	1.096
	D	1.081	.500	0.892	0.892	-.111	0.781
3) Ex-Post Global Optimum	A	1.400	.500	0.860	0.860	.620	1.480
	B	1.158	.558	1.129	0.666	.471	1.137
	C	1.158	.442	0.666	1.129	.008	1.137
	D	0.800	.500	0.920	0.920	-.100	0.820
4) Ex-Ante Global Optimum	A	1.361	.500	0.864	0.864	.615	1.479
	B	1.309	.565	1.148	0.624	.501	1.126
	C	1.309	.435	0.624	1.148	-.022	1.126
	D	0.891	.500	0.911	0.911	-.095	0.816

	q_1	q_2	π_1^*	π_2^*	$\partial W^{D*}/\partial I_1$	$\partial W^{D*}/\partial I_2$	$\partial W^{G*}/\partial I_1$	$\partial W^{G*}/\partial I_2$	W^{D*}	W^{G*}
1) Ex-Post Dom. Opt.	.611	.708	0.806	.797	.167	-.037	.057	.033	.289	1.085
2) Ex-Ante Dom. Opt	.746	.767	0.767	.763	.101	-.046	.020	.024	.327	1.090
3) Ex-Post Global Opt.	.649	.649	0.811	0.811	.140	-.023	.047	.047	.284	1.096
4) Ex-Ante Global Opt.	.707	.707	0.791	0.791	.113	-.040	.030	.030	.313	1.104

Table 2. Numerical Results with Technology Transfer and Monotonic Standards

	State z	s_z	θ_z	TT[B]	π_{1z}	π_{2z}	W_z^D	W_z^G
1) Ex-Ante Domestic Optimum, Case 1	A	1.311	.555		1.590	0.923	.956	1.879
	B	1.311	.592		1.840	0.737	.895	1.632
	C	1.311	.519	x	1.355	1.158	.721	1.879
	D	1.141	.555		1.624	0.957	.373	1.330
2) Ex-Ante Global Optimum, Case 1	A	1.079	.555		1.636	0.969	.932	1.901
	B	1.079	.586		1.841	0.815	.880	1.695
	C	1.079	.526	x	1.442	1.164	.737	1.901
	D	0.859	.555		1.680	1.013	.429	1.443
3) Ex-Ante Domestic Optimum, Case 2 [A]	A	1.480	.500		0.852	0.852	.625	1.477
	B	1.480	.574		1.170	0.578	.510	1.088
	C	1.461	.426		0.583	1.167	-.074	1.093
	D	1.080	.500		0.892	0.892	-.111	0.781

	q_1	q_2	π_1^*	π_2^*	W^{D*}	W^{G*}
1) Ex-Ante Dom. Opt., Case 1	.556	.481	1.538	0.862	.673	1.534
2) Ex-Ante Global Opt., Case 1	.421	.323	1.616	0.940	.633	1.573
3) Ex-Ante Dom. Opt., Case 2	.742	.745	0.768	0.767	.325	1.093

[A]In case 2, the monotonicity constraint on standards ensures that technology does not transfer. Moreover, because the monotonicity constraint on standards does not bind in the ex-ante global optimum for case 2, the ex-ante global optimum for this case is the same as described in Table 1B.
[B] The "TT" column indicates whether technology transfer occurs (with "x" indicating transfer). When transfer occurs, reported profits and welfares account for benefits of technology sale with the technology seller obtaining all gains from trade.

Table 3. Numerical Results with Technology Transfer, Monotonic Standards, and Transfer Subsidies

	State z	s_z	θ_z	TT/S[A]	π_{1z}	π_{2z}	W_z^D	W_z^G
1) Ex-Ante	A	1.351	.555		1.582	0.915	.955	1.870
Domestic	B	1.351	.593	.067	1.840	0.723	1.080	1.803
Optimum,	C	1.351	.518	x	1.340	1.157	.713	1.870
Case 1	D	1.121	.555		1.624	0.957	.374	1.341
2) Ex-Ante	A	1.142	.555		1.623	0.957	.944	1.900
Global	B	1.142	.587	.054	1.841	0.794	1.052	1.846
Optimum,	C	1.142	.524	x	1.418	1.162	.738	1.900
Case 1	D	0.872	.555		1.677	1.011	.428	1.439
3) Ex-Ante	A	1.490	.500		0.851	0.851	.625	1.476
Domestic	B	1.490	.575	.044	1.171	0.575	.856	1.432
Optimum,	C	1.490	.425	.044	0.575	1.171	.260	1.432
Case 2	D	0.960	.500		0.904	0.904	-.097	0.807
4) Ex-Ante	A	1.359	.500		0.864	0.864	.615	1.479
Global	B	1.359	.568	.037	1.154	0.611	.831	1.442
Optimum,	C	1.359	.432	.037	0.611	1.154	.288	1.442
Case 2	D	0.759	.500		0.924	0.924	-.105	0.819

	q_1	q_2	π_1^*	π_2^*	W^{D*}	W^{G*}
1) Ex-Ante Domestic, Case 1	.559	.483	1.534	0.856	.726	1.582
2) Ex-Ante Global, Case 1	.440	.361	1.604	0.927	.690	1.617
3) Ex-Ante Domestic, Case 2	.744	.744	0.767	0.767	.457	1.224
4) Ex-Ante Global, Case 2	.716	.716	0.788	0.788	.446	1.235

[A] The "TT/S" column indicates an unsubsidized technology transfer with an "x" and a subsidized transfer with the amount of government subsidy. When unsubsidized transfer occurs, reported profits and welfares account for benefits of technology sale with the technology seller obtaining all gains from trade. When subsidized transfer occurs, reported welfares account for benefits of technology exchange, less government costs of subsidy.