Cardon Research Papers
in Agricultural and Resource Economics

Research Paper 2006-02
May 2006

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

Robert Innes
The University of Arizona

Department of Agricultural and Resource Economics
College of Agriculture and Life Sciences
The University of Arizona

This paper is available online at http://ag.arizona.edu/arec/pubs/workingpapers.html

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

By Robert Innes, University of Arizona*

Abstract

We study a model of differentiated product competition by domestic and foreign firms that invest in environmental R&D in order to reduce costs of complying with government pollution standards. In this setting – and despite an absence of knowledge spillovers or other explicit sources of market failure in research – we find that optimal standards may often satisfy the "Porter Hypothesis" in two senses: (1) post-innovation (ex-post) environmental standards that maximize 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 to pollution abatement standards that exceed their ex-post optimal levels.

*Robert Innes, Departments of Economics and Agricultural and Resource Economics, University of Arizona, Tucson, AZ 85721, Phone: (520) 621-9741, FAX: (520) 621-6250, email: innes@ag.arizona.edu.

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. 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.

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 tightest 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 three 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 has 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, with tight environmental regulations somehow imparting an advantage to China’s domestic automobile industry relative to its international competition, perhaps via 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 (and the Porter Hypothesis) in the following respects. First, in the domestic market to which environmental regulations apply, both domestic and foreign producers compete. 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. By making technology endogenous, we raise an additional issue as well: Considering impacts on R&D outcomes, will a domestic planner set tighter standards than are globally optimal?

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. Graeker (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. MacAusland (2004) 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." Moreover, even when a version of the Porter Hypothesis can prevail due to the logic of "raising rivals' costs" in international trade, the ultimate prescription of these models may be quite the opposite of Porter's; because strategic competition between countries in the setting of export subsidies is disadvantageous, international welfare can be enhanced by international agreements that limit the subsidies; in other words, while individual countries may be unilaterally better off with a tighter environmental policy that aids its domestic industry, they would prefer a world in which neither they nor their international rivals subsidize exports via environmental policy distortions.

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 R&D investments that increase the likelihood of discovering a low-polluting, low-production-cost technology; environmental regulation can mitigate this agency problem, promoting more R&D. Mohr (2002) instead posits a "learning-by-doing" externality associated with the adoption of a new "clean" technology; this externality gives rise to a beneficial role for the government in promoting the adoption of the new technology with strong environmental policy. Hart

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

(2004) argues that environmental taxes can increase economic growth by spurring R&D that is otherwise underprovided due to plausible knowledge spillovers that private firms do not internalize.

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 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 (see also Feichtinger, et al., 2005). 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 Graeker (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.

This paper is also closely 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 relevant here. First, although most of the literature focuses on models of competitive industries with a patent-protected (and hence, imperfectly competitive) R&D sector, a subset of papers models R&D and price or output competition in oligopolistic environments, as in the present paper (and as seems appropriate for study of the Porter Hypothesis). Montero (2002a, 2002b) studies how different policy instruments affect R&D incentives under different market structures (Cournot and Bertrand). Katsoulacos and Xepapadeas (1996) consider a Cournot duopoly wherein the firms engage in environmental R&D; one firm's R&D has spillover benefits to the other firm; and the government can commit ex-ante to an emission tax and R&D subsidy. These authors find that the optimal emission tax is below its Pigovian level (to help correct excessively high output prices);[2] provided R&D spillovers are sufficiently large, the optimal R&D subsidy is positive. Innes and Bial (2002) come to a similar conclusion in a Bertrand model of the output market wherein (contrary to Katsoulacos and Xepapadeas, 1996) R&D cannot be directly regulated, but the government can set both emission taxes and standards. Again a low emission tax helps correct prices that are "too high," and standards serve to avoid resulting incentives

[2] See also Feess and Taistra (2000). Parry (1995), among others, obtains a related result when R&D cannot be directly regulated (taxed or subsidized). Parry (1995) finds that the optimal emission tax is less than its Pigovian level in order to correct the excessively high prices that result from equilibrium (monopoly)

for excessive pollution; however, standards are only distorted "off equilibrium" in order to deter the excessive R&D that otherwise prevails. With regard to the Porter Hypothesis, this work is either agnostic (Montero, 2002) or at odds (Katsoulacos and Xepapadeas, 1996; Innes and Bial, 2002). By studying a model of differentiated product competition regulated by environmental standards (as comports with predominant practice), the present paper comes to a different conclusion.

Second, a small strand of the literature considers alternative government commitment strategies in the setting of environmental policies. Amacher and Malik (2002) compare an emission tax selected either ex-ante (before R&D decisions are made) or ex-post (after R&D). Denicolo (1999) compares effluent taxes and pollution permits under the same two commitment options. Unlike this earlier work (but like Innes and Bial, 2002), Requate (2005b) also allows the regulator to commit ex-ante to a menu of technology-contingent emission tax rates (or pollution permit quotas). Because a menu of policy settings can always replicate policies under other commitment options, Requate (2005b) finds that efficiency can be enhanced by the ability to make ex-ante (menu) commitments. 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. Interestingly, in this model, if the government selects the emission tax after R&D occurs, but before adoption decisions are made, the government will wish to set the tax higher than its Pigovian level – a result that might seem to accord with the Porter Hypothesis and contradict conclusions of Parry (1995) and others. The explanation for this result is that the monopoly patent-holder over-prices the technology, leading to less

license fees by the holder of the new environmental compliance technology. Such results represent clever extensions of the literature on optimal emission taxes under monopoly (e.g., Barnett, 1984, and others).

adoption than is efficient; raising the effluent tax raises the demand for the technology and thus helps offset the suboptimal extent of adoption. However, this conclusion does not extend to the case of full ex-ante (menu) commitment, where the government adjusts its menu to motivate more efficient R&D decisions. In contrast, in the present paper – where we instead focus on environmental standards and R&D by differentiated product producers – we find that the Porter Hypothesis may well be supported in an ex-ante sense.

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 standard Hotelling address model wherein N consumers each demand one unit of product. 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) uniformily 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) $\theta_m = (1/2) + ([K+P_2-P_1]/2t)$, where $K \equiv V_1-V_2$.

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

<u>Assumption 1</u>: $K \geq 0$.

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. Whatever the nature of the standard, 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 = 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 $F'\geq 0$, $F''\geq 0$, and $F'''\geq 0$ (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

[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.

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 production in the domestic market is fixed, these benefits can be measured simply by the function B(s), where $B'>0$, $B''<0$ and $B'''\leq 0$ (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 ($\delta=1$) and failure ($\delta=0$). A higher firm investment in R&D, I_i, raises the probability of success, $q(I_i)$, where $q'(I)>0$ and $q''(I)<0$ (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 with how a domestic government that maximizes domestic welfare – ignoring effects on foreign firm profits – will choose these four standards. Several questions arise.

The first set of questions concerns ex-post choices of standards – that is, when the government chooses standards to maximize 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)?

The second set of questions concerns 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. Because trade agreements limit such explicit domestic subsidies, we focus on a policy regime that only regulates the environment (with standards).

Fifth, we ignore cross-country effects of standards. Domestic standards are implicitly assumed to have no spillovers in delivery of products to foreign markets, either directly or via induced technology change. For example, if standards and associated technologies are quite specific to the domestic market, there will be no cross-border spillovers. Of course, there are examples in which one might expect cross-country effects. Our positive analysis is quite easily extended to consider exogenous effects of technology change on firms' profits in foreign markets, as arguably is the relevant case for Chinese automotive emission regulations. We discuss such effects in Section VI. 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. For example, we will later see that technology transfer does not occur when the pro-domestic preference (K) is sufficiently small and environmental standards do not fall with improvements in environmental technology. Even in these cases, of course, the government may want to promote the transfer of technology from one firm to the next in the event that only one firm succeeds in its R&D. We consider such policy options in Section VI below.

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) $$c_1 = c(s, \delta_1) \quad , \quad c_2 = c(s, \delta_2) \quad \rightarrow \quad \Delta = \text{cost difference} = c_1 - c_2.$$

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

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

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

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

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

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

Ignoring constants, domestic welfare is thus:

$$W^D = (K-\Delta)\, \theta_m - c_2 - \pi_2(\Delta,s) \;\; - rI_1 + t\, \theta_m (1- \theta_m) + B(s) - 2F(s). \tag{5}$$

Global welfare adds back foreign firm profit:

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

<u>III. Ex-Post Optimal Regulation</u>

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):

$$\partial W^D/\partial s = -(\partial\Delta/\partial s)(\theta_m + (1/3)) + B' - F' - \partial c_2/\partial s = 0. \tag{7}$$

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

$$\begin{aligned} \partial W^G/\partial s &= \partial W^D/\partial s + (2/3)(\partial\Delta/\partial s)(1-\theta_m) - F' \\ &= (\partial\Delta/\partial s)[(1-5\theta_m)/3)] + B' - 2F' - \partial c_2/\partial s = 0. \end{aligned} \tag{8}$$

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) $(2/3)(\Delta_s)(1-\theta_m) - F' < (>)\ 0 \quad \Leftrightarrow$

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 (δ_1=δ_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 $\theta_m <1$ (by Assumption 2) and $F' \geq 0$, we have:

Proposition 1. 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. 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).

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.

Proposition 1 might be interpreted 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.

We now turn to a number of positive implications for the effects of technology on regulatory policy. First, how do optimal standards respond to domestic vs. foreign innovation?

Proposition 2. Domestically optimal standards rise more with successful domestic innovation than they do with successful foreign innovation:

$$s_B^D > s_C^D \iff s_B^D - s_D^D > s_C^D - s_D^D \quad , \quad s_A^D - s_C^D > s_A^D - s_B^D .$$

If and only if K>0, globally optimal standards rise more with domestic innovation than with foreign innovation:

$$K > (=)\ 0 \iff s_B^G > (=)\ s_C^G .$$

For the domestic planner, the ability to "raise the rival's costs" provides an added motive for a higher standard in state B, and for a lower standard in state C, even when consumers have no overall preference for the domestic product (K=)). Raising the standard in state B (when the domestic firm has the better technology) and lowering it in state C (when the foreign firm has the better technology) advantages the domestic (vs. foreign) firm, as desired by the domestic planner. When consumers have preference for the domestic product (K>0) – so that the domestic firm has a larger market share, ceteris paribus – then domestic (vs. foreign) innovation lowers costs of environmental compliance for a larger share of the market, also favoring a higher standard in state B. Because only the second (market share) effect is relevant to the global planner, a positive K is necessary for globally optimal standards to rise more in state B.

Second, do standards necessarily rise with technological improvement?

Proposition 3. (A) Domestically optimal standards rise with domestic innovation or uniform innovation by both firms: $s_B^D > s_D^D$, $s_A^D > s_C^D$, and $s_A^D > s_D^D$. Domestically optimal standards also rise with foreign innovation, provided the foreign firm market share is at least one-third:

$$\theta_m(\Delta_C) < (>)\ (2/3) \quad \Leftrightarrow \quad s_C^D > (<)\ s_D^D$$

$$\theta_m(\Delta_B) < (>)\ (2/3) \quad \Leftrightarrow \quad s_A^D > (<)\ s_B^D$$

where $\Delta_B = \Delta^*(s) \equiv c(s,1)\text{-}c(s,0)$ at $s = s_B^D$ and $\Delta_C = -\Delta^*(s)$ at $s = s_C^D$.

(B) Globally optimal standards rise with (i) domestic innovation alone or innovation by both firms, $s_B^G > s_D^G$ and $s_A^G > s_D^G$; (ii) domestic innovation, given foreign innovation, provided domestic market share is at least one-fifth,

$$\theta_m(\Delta_C) > (<)\ (1/5) \quad \Leftrightarrow \quad s_A^G > (<)\ s_C^G\ ;$$

and (iii) foreign innovation, provided the foreign firm market share is at least one-fifth,

$$\theta_m(\Delta_C) < (>)\ (4/5) \quad \Leftrightarrow \quad s_C^G > (<)\ s_D^G$$

$$\theta_m(\Delta_B) < (>)\ (4/5) \quad \Leftrightarrow \quad s_A^G > (<)\ s_B^G,$$

where $\Delta_B = \Delta^*(s_B^G)$ and $\Delta_C = -\Delta^*(s_C^G)$.

For the domestic planner, foreign innovation gives rise to two effects on standard setting incentives: (1) it motivates lower standards either to attenuate the foreign firm's cost advantage (in state C) or because it vitiates "raising rival's costs" incentives for higher standards (when moving from state B to state A), and (2) it motivates higher standards by lowering the foreign firm's cost of environmental compliance. The second effect is larger when the foreign firm has a larger market share and, hence, dominates when the foreign firm is sufficiently big.

For the global planner, one might expect only the second effect to be in force. However, due to imperfect competition, firm prices do not precisely reflect relevant cost differences between firms; the net effect of this competition is to under-weight the net advantage of the domestic firm, $K-\Delta$, in the determination of market share; hence, whenever $K-\Delta>0$ (and hence, $\theta_m > 1/2$), the global planner has an incentive to raise the domestic market share in his standard-setting calculus. This can only be done in the asymmetric technology states B and C wherein standards affect firm cost differences and, hence, pricing. The upshot (when $K-\Delta>0$) is that the global planner has an incentive to lower the standard in state C and raise it in state B, in order to bring domestic market share closer to its optimal level.[4] Hence, as with the domestic planner (but to a lesser extent), standards rise with foreign innovation only if the compliance-cost-reduction effect of innovation – which favors higher standards and rises with foreign market share – is sufficiently strong.

Third, how does foreign innovation affect the extent to which standards respond to domestic innovation, and vice versa?

<u>Proposition 4</u>. Let us suppose that $s_A^D \geq s_B^D$ (and $s_A^G \geq s_B^G$). Domestically (globally) optimal standards respond more to domestic (foreign) innovation when there is no foreign (domestic) innovation,

[4] The careful reader may be puzzled by the combination of this logic with the Proposition 2 conclusion that $s_B^G = s_C^G$ when K=0. However, when K=0, $K-\Delta=\Delta^*<0$ in state C and $K-\Delta=-\Delta^*>0$ in state B; hence, in this case, domestic market share is too high in state C and too low in state B, motivating higher standards in both states; indeed the effect is symmetric in the two states, thus motivating common standards. This

$$s_B^D - s_D^D > s_A^D - s_C^D \quad (\Rightarrow s_C^D - s_D^D > s_A^D - s_B^D),$$

$$s_B^G - s_D^G > s_A^G - s_C^G \quad (\Rightarrow s_C^G - s_D^G > s_A^G - s_B^G).$$

Although its proof is rather complicated, Proposition 4 follows from two forces: (1) diminishing returns to higher standards (pollution abatement); and (2) incentives to raise standards in state B in order to advantage the domestic firm.

Fourth and finally, how do standards depend upon the preference for domestic product (K) and attendant domestic market share?

Proposition 5. A greater domestic preference (higher K) leads to (i) higher optimal standards in state B, (ii) lower optimal standard in state C, and (iii) no change to standards in the symmetric technology states A and D:

$$d\,s_B^D/dK > 0,\ \ d\,s_B^G/dK > 0,\ \ d\,s_C^D/dK < 0,\ \ d\,s_C^G/dK < 0,$$

$$d\,s_A^D/dK = d\,s_A^G/dK = d\,s_D^D/dK = d\,s_D^G/dK = 0.$$

When the domestic preference K is higher, the market share of the technology winner is higher in state B (when the domestic firm wins) and lower in state C (when the foreign firm wins). Because the overall compliance-cost-reducing effect of the winner's victory grows with the winner's market share, a higher K yields greater economic benefits from raised standards in state B and reduced benefits from elevated standards in state C. In the symmetric technology states, both firms enjoy the same compliance cost reductions; hence, relative market share (and K) are irrelevant to a social planner's optimization.

IV. Innovation and Ex-Ante Optimal Regulation

---

discussion above implicitly assumes that K-Δ is positive in all states, implying a desire always to raise domestic market share on the part of a global planner.

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

$$\text{(9a)} \quad I_1: \ \max_{I} \ \pi_1^*(I;I_2) \equiv \sum_z q_z(I,I_2)\,\pi_{1z} - rI \ \Rightarrow \ I_1 = I_1^{**}(s_A, s_B, s_C, s_D;I_2),$$

$$\text{(9b)} \quad I_2: \ \max_{I} \ \pi_2^*(I;I_1) \equiv \sum_z q_z(I_1,I)\,\pi_{2z} - rI \ \Rightarrow \ I_2 = I_2^{**}(s_A, s_B, s_C, s_D;I_1),$$

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 (9a) and (9b),

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

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. For example, in some states, the government may want to commit to tighter standards in order to spur more domestic investment in R&D; in essence, this is the Porter conjecture.

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:

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

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:

Proposition 6. 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

$$B'(0) - F'(0) - c_s(0,0) \geq -(1/2)\, \Delta_s(s_A^D).$$

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.

Proposition 6 is the essential foundation of the Porter hypothesis, motivating some deviations from ex-post optimal standards in order to spur domestic R&D. Unfortunately, little can be said in general about how standards will be revised to achieve the ends suggested by Proposition 6. 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 (9a) and appealing to second order conditions):

(14a) $$\partial I_1^{**}(.;I_2)/\partial s_A \stackrel{s}{=} d\pi_{1A}/ds_A \leq 0 \ (<0 \text{ if } F'(s_A)>0),$$

(14b) $$\partial I_1^{**}(.;I_2)/\partial s_B \stackrel{s}{=} d\pi_{1B}/ds_B \quad (>0 \text{ if } d\pi_{1B}/ds_B > 0),$$

(14c) $$\partial I_1^{**}(.;I_2)/\partial s_C \stackrel{s}{=} - d\pi_{1C}/ds_C > 0,$$

(14d) $$\partial I_1^{**}(.;I_2)/\partial s_D \stackrel{s}{=} d\pi_{1D}/ds_D \geq 0 \ (>0 \text{ if } F'(s_D)>0).$$

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') 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; by Proposition 6, the government generally seeks less foreign R&D at the margin, not more. Hence, 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 (14) – and hence, the associated version of the Porter hypothesis (higher standards for states B-D) – can be supported.

V. A Numerical Example

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. [5]

[5] 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 $\theta_m \in (0,1)$.

This example gives rise to closed form ex-post optimal standards.[6] 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,

(15a) I_1: $(1-q_1)\ \{q_2(\pi_{1A}-\pi_{1C})+(1-q_2)(\ \pi_{1B}-\pi_{1D})\} - r = 0,$

(15b) I_2: $(1-q_2)\ \{q_1(\pi_{2A}-\pi_{2B})+(1-q_1)(\ \pi_{1C}-\pi_{2D})\} - r = 0,$

where $(1-q_i) = q_i'$ for $q_i=1-e^{-I}$. In general, (15) can be solved for equilibrium success probabilities, $\{q_1, q_2\}$, and attendant investments, $I_i = -\ln(1-q_i)$.[7]

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.[8]

We consider a rather wide range of alternative parameter settings.[9] 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 domestic preference (with K=1<t=3), and 2) an alternative case in which there is no domestic preference

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

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

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

[7] 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.

[8] 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.

[9] 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 $r\in\{.07,.1\}$.

(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).[10]

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, the results illustrate many of our prior propositions. 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). Per Proposition 2, domestic optimal standards respond more to innovation by the domestic firm than to innovation by the foreign firm ($s_B^D > s_C^D$), even when the former enjoys no preference advantage over the latter (K=0, as in Case 2); likewise for global optimal standards, but only when the domestic firm enjoys a preference advantage (i.e., not in Case 2). Standards respond more to domestic innovation when the domestic firm is the only innovator (Proposition 4). And, as indicated by Proposition 6, domestic welfare rises with marginal domestic R&D and falls with marginal foreign R&D; global welfare rises with both.

In the illustrative cases, all of these properties persist in the ex-ante optima. Interestingly, however, the extent to which standard are more responsive to domestic vs.

[10] 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,

foreign R&D is drastically reduced. Thereason is that elevations in the state C standard (when the foreign firm is the lone innovator) are useful to spur domestic R&D. Note, in addition, that because the ex-ante optimum spurs both domestic R&D (which raises domestic welfare) and foreign R&D (which lowers it), domestic benefits of marginal domestic R&D fall, and domestic costs of marginal foreign R&D rise, when moving from ex-post to ex-ante domestic optima.

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. One might suspect that the opposite should be true, viz, when there is no preference advantage for either firm (K=0, as in Case 2), the domestic firm 1 invests more in R&D because its innovative success (in state b) is rewarded more than is the foreign firm's (in state C), with $s_B^D > s_C^D$. However, while the benefit to innovative success is greater to firm 1 (vs. 2) when it is the sole technology winner, one must also consider the firm's benefit of avoiding the other firm's lone success. For example, firm 2 benefits from avoiding state B when it succeeds in its R&D; likewise, firm 1 benefits from avoiding state C. Because standards are more lax in state C than in state B, firm 2 benefits more from avoiding state B than firm 1 benefits from avoiding state C. Hence, firm 2 may well have the greater incentive to invest in R&D, as illustrated in Case 2.[11]

---

b_0=2, α=.6, f=.1, and r=.07.

[11] 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

Fourth and finally, a modest point illustrated by Case 1. In the ex-post domestic optimum (vs. the global counterpart), generally higher environmental standards spur more environmental R&D. This salutary effect of domestic regulation can yield a higher level of average global welfare in the ex-post domestic optimum than in the ex-post global optimum (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. Extensions

A. Innovative Effects on Fixed Costs. For simplicity, we have assumed that the environmental technology only affects variable costs of production ($c(s,\delta)$), not fixed costs ($F(s)$). Little changes if technology also lowers fixed costs, with $F=F(s,\delta)$, $F_\delta<0$, and $F_{s\delta}\leq 0$. Vis-à-vis our invariant-fixed-cost specification ($F(s,1)=F(s,0)=F(s)$), these technology effects prompt the domestic social planner to set higher ex-post (optimal) standards in states A and B (due to the effects of domestic firm innovation in reduced marginal fixed costs of standards) and make no changes in states C and D (when the domestic firm achieves no innovation). The global planner also elevates standards in state C (due to the effects of foreign firm innovation in reducing its marginal fixed costs of standards). However, our conclusions on the relationships between ex-post domestic and global optimal standards persist (Proposition 1), as do the relationships between domestic ex-post optimal standards described in Propositions 2-5.

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).

Technology sensitive fixed costs also preserve the domestic social planner's desire to increase domestic firm R&D from the level elicited in the ex-post domestic optimum. The reason is that technology effects on domestic firm fixed costs have symmetric effects on domestic welfare and domestic firm profit; hence, relative R&D investment incentives are not qualitatively altered. However, technology sensitivity of fixed costs adds a motive for foreign firm R&D (directly lowering fixed costs, $F_\delta<0$) that is irrelevant to the domestic planner; as a result, the domestic planner has an added interest in lowering foreign R&D from the level produced by the ex-post domestic optimal policy regime.

B. Exogenous Benefits of Innovation in Foreign Markets. As noted at the outset, we do not consider cross-country spillovers in this paper. However, it is not particularly difficult to add exogenous benefits of new technologies in foreign markets, $\pi_1^F(\delta_1,\delta_2)$ and $\pi_2^F(\delta_1,\delta_2)$ for the domestic and foreign firm, respectively. Clearly, such exogenous benefits have no effect on ex-post optimal standards (because they are invariant to these standards). Moreover, because the domestic firm's benefits are added to both its profits and to domestic social welfare, these technology effects have no impact on relative incentives for domestic R&D for the domestic firm vis-à-vis the domestic social planner (Proposition 6). However, the foreign firm's benefits, $\pi_2^F(\delta_1,\delta_2)$, will rise when it successfully innovates, providing an added incentive for the firm to invest in R&D. Because the domestic planner does not share this benefit, it has an added interest in lowering foreign firm R&D from the level elicited by the ex-post domestic optimal policy regime (reinforcing Proposition 6).

C. Constraints on Rewarding Innovation. We have assumed that the government can freely choose standards in the four technology states. As illustrated in the numerical example, this freedom 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 such an incentive requires the plausible restriction that standards do not fall with more innovation; that is, $s_A \geq \max(s_B, s_C)$.

For our two numerical cases, imposing this monotonicity constraint on standards yields the ex-ante domestic optimal outcomes reported in Table 2. Comparing outcomes for Case 1 in Tables 1 and 2, we see that the monotonicity constraint leads to higher standards in some states and lower standards in others. In Case 1, for example, standards are higher in states A and D, and lower in states B and C, vis-à-vis the uncontrained ex-ante optimum. Vis-à-vis the ex-post optimum, the standards still falls in state A and rises in states C and D, but changes little in State B. Interestingly, in Case 1, the monotonicity constraint binds for both states B and C; hence, any innovation – whether by the domestic firm, the foreign firm, or both – leads to exactly the same change in the standard.

Notably, both of the illustrative cases in Table 2 continue to exhibit a form of the Porter hypothesis: Even with monotonicity constraints, the government commits to higher standards, in some states, in order to spur more environmental R&D. In both cases, for example, the government tightens standards in states C and D (vis-à-vis the ex-post optimum). For Case 1, we will see shortly that allowing for technology transfer yields a particularly strong form of the Porter hypothesis, with standards rising in all technology states.

D. Technology Transfer. We have thusfar assumed that, when only one firm succeeds, the technology cannot be transferred to the other firm. For example, if the transfer of technology is costly, then it will only occur if the joint profit gains to transfer exceed the costs. We implicitly assume in the foregoing analysis that transfer costs are large.

Let us 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:

Proposition 7. (A) If $s_A \geq s_B$ or if marginal fixed costs (F') 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.

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

Under certain circumstances, Proposition 7 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. However, these 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 $\pi_1+\pi_2$ higher in states B and C than in state A). However, if costless, technology transfer will occur in both states B and C of 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 split equally between the two firms.[12] 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 implausible. As noted above, there is reason to believe that standards cannot decline with technological improvement.

Let us instead suppose that standards are constrained to be monotonic in technology (as in Table 2). Then allowing technology transfer yields the ex-ante (Case 1) optima described in Table 3.[13] Particularly notable about the domestic optimum here is that it supports a very strong form of the Porter hypothesis: in every technology state,

---

[12] For example, 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: $\pi^*_{1B} = \pi_{1B}+(G_B/2)$, $\pi^*_{2B} = \pi_{2B}+(G_B/2)$.

[13] 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. Hence, with or without technology transfer, the monotonicity-constrained ex-ante optimum remains as described in Table 2.

standards are higher than in the ex-post optimum. In both the domestic and global optima, note that technology transfer occurs in state C – when societal gains from transfer are particularly large – but not in state B where the domestic firm retains its technological advantage. Moreover, comparing Tables 2 and 3, we see that the prospect of technology transfer raises standards in all technology states and permits substantial improvements in both domestic and global welfare.

The rise in standards in states A-C is directly attributable to the technology transfer in state C; because the state C standard is not actually implemented, ex-post welfare costs of raising the standard evaporate. Hence, incentives to elevate s_C, in order to spur more domestic R&D, rise. The monotonicity constraint in turn requires that the A standard be raised in tandem, which yields the ancillary benefit of permitting a higher B standard as well. The rise in the state D standard follows from different logic. With technology transfer, the associated revision in standards and R&D investments, the probability that state D arises is smaller (at least for the case examined here); as a result, the welfare cost of raising s_D, in order to spur more domestic R&D, is lower.

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 case described in Table 3, 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 = .0612. 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 = $(\pi_{1B}+\pi_{2B})-(\pi_{1A}+\pi_{2A}) = .065$

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. [14]

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 net gains equally shared by the two firms (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 4 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

[14] In cases such as this – when private technology exchange does not occur – the government will prefer to offer the minimum possible subsidy that elicits technology transfer, rather than nay higher level of subsidy. The reason is that portions of any higher subsidy are lost to the foreign firm.

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 3 and 4); as with unsubsidized (state C) technology transfer, a subsidized state B transfer eliminates the ex-post welfare cost of elevating s_B in order to spur R&D.

E. Third Party Innovation. Throughout the paper, we have focused on R&D by producing firms rather than third-party innovators. Our structure is arguably plausible for the concentrated industries of interest in this paper and also natural for purposes of our examination of the Porter Hypothesis. However, as Requate (2005) points out, there are industries in which one might expect R&D to be performed by a separate research sector. While a full treatment of third party innovation will not be attempted here, we can make some preliminary observations.

Consider a single (monopoly) R&D firm that, when successful in its R&D, can sell the new environmental technology to either or both of our two (foreign and domestic) firms. Further, let us suppose that standards are monotone in technology (so that $s_A \geq s_z$ for $z \in \{B, C, D\}$); no technology transfer subsidies are made; technology transfer does not occur (because, for example, K=0, per Corollary 2, or transfer costs are large); and the domestic firm, when it is the sole owner of the new technology, earns profit that rises with higher environmental standards, $\partial\pi_{1B}/\partial s_B > 0$ (because, for example, marginal fixed costs of environmental compliance are sufficiently small). Then, denoting the share of transfer rents that accrue to the monopoly R&D firm by $\beta_m \in (0,1]$, this firm has three options when it is successful in its R&D: (1) sell to both producers, earning rents equal to

$$R_{12} = \beta_m(\pi_{1A} + \pi_{2A} - \pi_{1D} - \pi_{2D});$$

(2) sell to the domestic firm 1 only, earning:

$$R_1 = \beta_m(\pi_{1B} - \pi_{1D});$$

or (3) sell to the foreign firm 2 only, earning

$$R_2 = \beta_m(\pi_{2C} - \pi_{2D}).$$

Under our posited circumstances, we have:

Proposition 8. Assuming no technology transfer, monotone standards, $\partial\pi_{1B}/\partial s_B>0$, $K>0$, and $s_B \geq s_C$, the successful R&D monopolist will sell its technology to the domestic firm 1 only: $R_{12} \leq 0$, $R_1>0$, and $R_1>R_2$.[15]

When the new technology is adopted by both firms, neither enjoys higher profits as the firms pass on the cost savings to consumers in the course of their price competition. However, when only one firm has the new technology, the firm retains much of the relative cost savings. Because the domestic firm is larger (with $K>0$) and/or enjoys some preferential treatment in standard setting (with $s_B>s_C$), its profit gains from the technology advantage are greater. Hence, the R&D firm can extract a higher license fee by selling to the domestic firm, and not its foreign rival.

Proposition 8 implies that the only relevant technology states are B (when the domestic firm is the sole technology owner) and D (when the R&D monopolist is unsuccessful). Without loss, let us suppose that the domestic government sets

$s_A=s_B=s_C \geq s_D$.[16] The question we now pose is how the government will set its two relevant standards (s_B and s_D) relative to their ex-post optimal counterparts. The government's choice problem is as follows:

$$\max_{sB,\, sD} q(I)\, W_B^D\ (s_B) + (1-q(I))W_D^D(s_D) - rI$$

$$\text{s.t.}\quad I = I^*(s_B,s_D) = \operatorname{argmax}\ q(I)\ \beta_m\ (\pi_{1B}(s_B) - \pi_{1B}(s_B)) - rI \quad , \quad s_B \geq s_D.$$

Proposition 9. In the solution to problem (17) (and again assuming $\partial\pi_{1B}/\partial s_B>0$), the government elevates both standards above their ex-post optimal levels, $s_B>s_B^D$ and $s_D>s_D^D$.

Intuitively, the R&D firm does not enjoy a number of the benefits of its successful innovation, including some of the profit gains that the domestic firm enjoys (when $\beta_m<1$), cost reductions passed on to consumers, and potential external benefits due to lower pollution. As a result, there is too little investment in research. This shortfall can be mitigated by elevating domestic firm profit in state B (when R&D is sold to the domestic firm) and lowering these profits in state D (when the R&D is not "sold"), both of which increase the license fee that the R&D firm can charge for its new technology and thereby increase its incentive to invest in research. Because higher standards have precisely these effects, we again have a rather strong version of the Porter Hypothesis, with research optimally spurred by elevated environmental standards in all technology states.

VII. Conclusion

[15] If K=0 and $s_B=s_C$, $R_1=R_2$ and, hence, the R&D firm is indifferent between selling only to firm 1 and selling only to firm 2. However, if either K>0 or $s_B>s_C$, then $R_1>R_2$.

[16] It can be shown that the government will not wish to set $s_C>s_B$ in order to induce technology sale to the foreign (vs. domestic) firm.

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 of the 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; Graeker, 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.

<u>Appendix</u>

<u>Proof of Proposition 2</u>. Define $\Delta^*(s)=c(s,1)-c(s,0)$. In state B, $\Delta=\Delta^*$; in state C, $\Delta=-\Delta^*$. Evaluating eq. (7) for state B (where $\Delta=\Delta^*$ and $c_2=c(s,0)$) at $s= s_C^D$ (where (7) holds with $\Delta=-\Delta^*$ and $c_2=c(s,1)$), we have (substituting for θ_m from (4)):

(A1) $$d W_B^D (s_C^D)/ds = - \Delta_s^* (2t+K)/3t > 0.$$

Similarly, evaluating eq. (8) for state B at $s= s_C^G$:

(A2) $$d W_B^G (s_C^G)/ds = - \Delta_s^* (5K)/9t.$$

Proposition 2 follows from (A1)-(A2) and concavity of W_B^D and W_B^G. QED.

<u>Proof of Proposition 3</u>. (A) As in the proof of Proposition 2, we have:

$$d W_B^D (s_D^D)/ds = - \Delta_s^*(s_D^D) (\theta_m(\Delta^*)+(1/3)) > 0.$$

$$d W_A^D(s_C^D)/ds = - \Delta_s^*(s_C^D) (\theta_m(-\Delta^*)+(1/3)) > 0.$$

$$d W_A^D(s_D^D)/ds = - \Delta_s^*(s_D^D) > 0.$$

$$d W_C^D(s_D^D)/ds = \Delta_s^*(s_D^D) (\theta_m(-\Delta^*)-(2/3)) > (<) 0 \Leftrightarrow \theta_m( ) < (>) 2/3.$$

$$d W_A^D(s_B^D)/ds = \Delta_s^*(s_B^D) (\theta_m(\Delta^*)-(2/3)) > (<) 0 \Leftrightarrow \theta_m( ) < (>) 2/3.$$

(B) For the global optimum, we have:

$$d W_B^G(s_D^G)/ds = \Delta_s^*(s_D^G) (1-5\theta_m(\Delta^*))/3 > 0.$$

$$d W_A^G(s_C^G)/ds = \Delta_s^*(s_C^G) (1-5\theta_m(-\Delta^*))/3 > (<) 0 \Leftrightarrow \theta_m( ) < (>) 1/5.$$

$$d W_A^G(s_D^G)/ds = -\Delta_s^*(s_D^G) > 0.$$

$$d\,W_C^G(s_D^G)/ds \;=\; -\Delta_s^*(s_D^G)\,(4\text{-}5\theta_m(-\Delta^*))/3 > (<)\ 0 \Leftrightarrow\ \theta_m(\ ) < (>)\ 4/5.$$

$$d\,W_A^G(s_B^G)/ds \;=\; -\Delta_s^*(s_B^G)\,(4\text{-}5\theta_m(\Delta^*))/3 > (<)\ 0 \Leftrightarrow\ \theta_m(\ ) < (>)\ 4/5.$$

The Proposition follows from the foregoing inequalities and concavity of the ex-post welfare functions. QED.

Proof of Proposition 4. Domestic Optimum. It suffices to show that $dW_D^D/ds<0$ at $s= s_C^D-(s_A^D-s_B^D)$, implying that $s_D^D< s_C^D-(s_A^D-s_B^D)$ as required. Defining $z = (s_A^D-s_B^D)\geq 0$, this requirement can be written:

$$\text{(A3)}\quad -\,dW_D^D(s_C^D\text{-}z)/ds = -\ \{\ dW_D^D(s_C^D)/ds\ -\int_{SC-z}^{SC} (d^2W_D^D(s)/ds^2)\,ds\ \}$$

$$> 0 = dW_A^D(s_B^D+z)/ds = \{\ dW_A^D(s_B^D)/ds\ +\int_{SB}^{SB+z} (d^2W_A^D(s)/ds^2)\,ds\ \},$$

where $SC= s_C^D$, $SB= s_B^D$, and the penultimate equality follows from $s_B^D+z= s_A^D$ and the definition of s_A^D. (A3) will h old provided two conditions are satisfied:

$$\text{(A4)}\qquad -\,dW_D^D(s_C^D)/ds\ > dW_A^D(s_B^D)/ds,\quad \text{and}$$

$$\text{(A5)}\qquad d^2W_D^D(s_0)/ds^2 \geq\ d^2W_A^D(s_1)/ds^2)\quad \text{for}\quad s_1\geq s_0.$$

Using eq. (7), we can rewrite (A4):

$$\text{(A4')}\quad dW_D^D(s_C^D)/ds\ + dW_A^D(s_B^D)/ds$$

$$= \Delta_s^*(s_B^D)\,(\theta_m(\Delta^*(s_B^D))\text{-}(2/3)) + \Delta_s^*(s_C^D)\,((2/3)\text{-}\theta_m(-\Delta^*(s_C^D))) < 0.$$

To establish the inequality in (A4'), note that:

$$\text{(A6)}\quad \left|\theta_m(\Delta^*(s_B^D))\text{-}(2/3)\right| = (2/3)\text{-}\theta_m(\Delta^*(s_B^D)) < (2/3)\text{-}\theta_m(-\Delta^*(s_C^D)) > 0,$$

where the equality is due to $s_A^D \geq s_B^D$ (and Proposition 3); the first inequality follows from the definition of θ_m in equation (4) and $-\Delta^*(s_C^D)>0>\Delta^*(s_B^D)$; and the last inequality follows from $s_A^D \geq s_B^D$, Proposition 3, and the first inequality. Further,

$$\text{(A7)} \quad |\Delta_s^*(s_B^D)| = -\Delta_s^*(s_B^D) = -\int_0^1 c_{s\delta}(s_B^D,\delta)\, d\delta$$

$$\leq -\int_0^1 c_{s\delta}(s_C^D,\delta)\, d\delta = -\Delta_s^*(s_C^D) = |\Delta_s^*(s_C^D)|,$$

where the inequality follows from $c_{ss\delta} \geq 0$ and $s_B^D > s_C^D$ (Proposition 2). (A6)-(A7) imply the inequality in (A4') (and hence, (A4)). To establish (A5), we have:

$$\text{(A8)} \quad d^2W_D^D(s_0)/ds^2 - d^2W_A^D(s_1)/ds^2)$$

$$= \{B''(s_0)-B''(s_1)\} - \{F''(s_0)-F''(s_1)\} - \{c_{ss}(s_0,0)-c_{ss}(s_1,1)\} \geq 0,$$

where the inequality is due to $s_1 \geq s_0$, $B''' \leq 0$, $F''' \geq 0$, $c_{ss}(s_1,1) \geq c_{ss}(s_1,0)$ (by $c_{ss\delta} \geq 0$) and $c_{ss}(s_1,0) \geq c_{ss}(s_0,0)$ (by $c_{sss} \geq 0$).

Global Optimum. Likewise for the global optimum, it suffices to satisfy the analogs to (A4) and (A5). Using equation (8), we have:

$$\text{(A4'')} \quad dW_D^G(s_C^G)/ds + dW_A^G(s_B^G)/ds$$

$$= (5/3)\{\Delta_s^*(s_B^G)\,(\theta_m(\Delta^*(s_B^G))-(4/5)) + \Delta_s^*(s_C^G)\,((4/5)-\theta_m(-\Delta^*(s_C^G))) < 0,$$

where the inequality in (A4'') follows from exactly the same logic as does the inequality in (A4). Further, we have for $s_1 \geq s_0$,

$$\text{(A8')} \quad d^2W_D^G(s_0)/ds^2 - d^2W_A^G(s_1)/ds^2)$$

$$= \{B''(s_0)-B''(s_1)\} - 2\{F''(s_0)-F''(s_1)\} - \{c_{ss}(s_0,0)-c_{ss}(s_1,1)\} \geq 0,$$

where the inequality follows from the same logic as for (A8). QED.

Proof of Proposition 5. Invariance of s_A^D, s_D^D, s_A^G, and s_D^G to K follows from Δ=0 in states A and D, and conditions (7)-(8) that define these optimal standards. Differentiating eq.s (7)-(8), and appealing to local second order conditions, we have:

$$d\, s_z^D/dK \overset{s}{=} -(6t)^{-1}\Delta_s \quad , \quad d\, s_z^G/dK \overset{s}{=} -(5/18t)\,\Delta_s \quad , \quad \text{for } z \in \{B,C\},$$

where $\Delta_s = \Delta_s^* < 0$ in state B and $\Delta_s = -\Delta_s^* > 0$ in state C. QED.

Proof of Proposition 6. 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):

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

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 Δ_A=c*(s,δ)-c(s,1), Δ_B=c*(s,δ)-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:

(A9a) $\quad W_z^{D**}(1) - \pi_z^{D*}(1) = W_z^o \quad , \quad z\in\{A,B\},$

(A9b) $\quad W_A^{D**}(0) - \pi_A^{D*}(0) = W_C^o \quad , \quad W_B^{D**}(0) - \pi_B^{D*}(0) = W_D^o.$

(A10) $d\,W_z^{D**}(\delta)/d\delta = \{(\partial W_z^{D*}(s_z^*(\delta),\delta)/\partial s) - (\partial F_z^*(s_z^*(\delta),\delta)/\partial s)\}(ds_z^*(\delta)/d\delta)$

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

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

We want to show that:

(A11a) $$W_B^o - W_D^o = \int_0^1 \{(dW_B^{D**}(\delta)/d\delta) - (d\pi_B^{D*}(\delta)/d\delta)\}\, d\delta > 0,$$

(A11b) $$W_A^o - W_C^o = \int_0^1 \{(dW_A^{D**}(\delta)/d\delta) - (d\pi_A^{D*}(\delta)/d\delta)\}\, d\delta > 0,$$

where the equalities follow from (A9). Expanding the right hand sides (using (A10)):

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

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

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

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

Hence,

(A12) $(dW_z^{D**}(\delta)/d\delta)$-$(d\pi_z^{D*}(\delta)/d\delta) = \{-\Delta^*(s_z^*(\delta))(1+\theta) + 2\theta(\partial\Delta_z()/\partial s)(ds_z^*(\delta)/d\delta)\}/3$.

Now, for z=A, the right hand side of (A12) 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 (A11b)). For z=B,

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

$$> (2\theta/3)\{-\Delta^* + \delta\, \Delta_s^* (s_B^D - s_D^D)\} \overset{s}{=} -\Delta^*(s_B^*(\delta)) + \delta\, \Delta_s^*(s_B^*(\delta))(s_B^D - s_D^D)\} \equiv X(\delta),$$

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

$$dX/d\delta = \delta\, (s_B^D - s_D^D)^2\Delta_{ss}^*(s_B^*(\delta)) \geq 0,$$

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 $W_B^o - W_D^o > 0$ (equation (A11a)).

Foreign R&D. It suffices to show:

$$W_C^o \equiv W_C^D - \pi_C^F < W_D^D - \pi_D^F \equiv W_D^o \quad \text{and} \qquad W_A^o \equiv W_A^D - \pi_A^F < W_B^D - \pi_B^F \equiv W_B^o.$$

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

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

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

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

$$\pi_z^{F*}(\delta) = 2t(1-\theta(\Delta_z^*))^2 - F(s_z^*(\delta)), \quad z\in\{A,C\},$$

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 $g_z(s, \delta)=\partial W_z^{D*}(s,\delta)/\partial s$ as before.

Now note:

(A9a') $\qquad W_z^{D**}(1) - \pi_z^{F*}(1) = W_z^o \quad , \quad z\in\{A,C\},$

(A9b') $W_A^{D**}(0) - \pi_A^{F*}(0) = W_B^o$, $W_C^{D**}(0) - \pi_C^{F*}(0) = W_D^o$.

(A10') $d\,W_z^{D**}(\delta)/d\delta = \{(\partial W_z^{D*}(s_z^*(\delta),\delta)/\partial\delta)-(\partial F_z^*(s_z^*(\delta),\delta)/\partial\delta)\}$, $z\in\{A,B\}$.

We want to show that:

(A11a') $$W_C^o - W_D^o = \int_0^1 \{(dW_C^{D**}(\delta)/d\delta)-(d\pi_C^{F*}(\delta)/d\delta)\}\, d\delta < 0,$$

(A11b') $$W_A^o - W_B^o = \int_0^1 \{(dW_A^{D**}(\delta)/d\delta)-(d\pi_A^{F*}(\delta)/d\delta)\}\, d\delta < 0,$$

Expanding the right hand sides:

$$dW_z^{D**}(\delta)/d\delta = \Delta^*(s_z^*(\delta))(\theta-(2/3)) - F'(s_z^*(\delta))(ds_z^*(\delta)/d\delta)$$

$$d\pi_z^{F*}(\delta)/d\delta = (2/3)(1-\theta)[- \Delta^*(s_z^*(\delta)) + (\partial\Delta_z/\partial s)(ds_z^*(\delta)/d\delta)] - F'(s_z^*(\delta))(ds_z^*(\delta)/d\delta),$$

where $\partial\Delta_A/\partial s = (1-\delta)\Delta_s^*(s_z^*(\delta)) \le 0$ and $\partial\Delta_C/\partial s = -\delta\Delta_s^*(s_z^*(\delta)) \ge 0$. Hence,

(A12') $\{(dW_z^{D**}(\delta)/d\delta)-(d\pi_z^{F*}(\delta)/d\delta) = \{\Delta^*(s_z^*(\delta))\theta - 2(1-\theta)(\partial\Delta_z()/\partial s)(ds_z^*(\delta)/d\delta)\}/3$.

Now, for z=C, the right hand side of (A12') is negative (with $\Delta^*<0$, $\theta>0$, $\theta<1$, $\partial\Delta_C()/\partial s\ge 0$, and $ds_C^*(\delta)/d\delta = s_C^D - s_D^D > 0$, given $K<t$ by assumption), establishing that $W_C^o - W_D^o < 0$ (equation (A11b')). For z=A, the right hand side is negative when $s_A^D \le s_B^D$ (with $\partial\Delta_A()/\partial s \le 0$ and $ds_A^*(\delta)/d\delta = s_A^D - s_B^D \le 0$ in this case). The remaining case is z=A with $s_A^D > s_B^D$; for this case, with $\theta \ge (1/2)$ (by $K \ge 0$ and $\delta_1 = 1 \ge \delta = \delta_2$, and hence, $\Delta_A \le 0$) and $(\partial\Delta_A/\partial s)(ds_z^*/d\delta) \le 0$,

$$(dW_B^{D**}(\delta)/d\delta)-(d\pi_B^{D*}(\delta)/d\delta) \le \{\Delta^* - 2(1-\delta)\Delta_s^* (s_A^D - s_B^D)\}(1/6) \equiv (1/6)\, X(\delta),$$

where

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

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

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

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

<u>Proof of Corollary 1</u>. 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:

$$\partial W^D_B /\partial s = B'\text{-}F'\text{-}c_s(s,0)((2/3)\text{-}\theta)\text{-}c_s(s,1)(\theta+(1/3)).$$

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

$$\partial W^D_B /\partial s > B'\text{-}F'\text{-}c_s(s,0)(1/6)\text{-}c_s(s,1)(5/6) \equiv J(s).$$

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

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

Where sa= s^D_A and sd=s^D_D, the equality substitutes from the first order conditions defining s^D_D (where B'-F'=c_s(s,0)) and s^D_A (where B'-F'=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 $s^D_D \geq (s^D_A/3)$ if the Corollary's second condition holds. Let

$$J(s) \equiv \partial W^D_D/\partial s > B' - F' - c_s(s,0).$$

By concavity of J,

$$J(s^D_A/3) \geq (1/3)\Delta^*_s(s^D_A) + (2/3)(B'(0) - F'(0) - c_s(s,0)).$$

Hence, if the Corollary's second condition holds, $\partial W^D_D/\partial s \geq 0$ at $s = s^D_A/3$. QED.

Proof of Proposition 7. Define

$$\Pi(\Delta_z) = \text{joint domestic and foreign firm profit before fixed costs}$$
$$= 2t\{\theta_m(\Delta_z)^2 ++(1-\theta_m(\Delta_z))^2\},$$

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

(A) It suffices to show:

$$\Pi(\Delta_B) - 2F(s_B) \geq \Pi(\Delta_A) - 2F(s_A), \tag{A13}$$

so that technology transfer is not profitable. Given our premises ($s_A \geq s_B$ or F' sufficiently small), (A13) will hold provided $\Pi(\Delta_B) > \Pi(\Delta_A)$. Now note:

$$\partial\Pi/\partial\Delta = (2/3)(1-2\theta_m) < (>)\ 0 \quad \text{as} \quad \theta_m > (<)\ (1/2). \tag{A14}$$

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 $\partial\theta_m/\partial\Delta<0$), (A14) 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 $\Delta_C>\Delta_A=0$), (A14) 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 7(A)-(B) are satisfied. QED.

Proof of Proposition 8. First, we have (with $s_A\geq s_D$):

$$R_{12} = 2\beta_m(F(s_B)-F(s_A))\leq 0.$$

Second, we have:

$$R_1 = \beta_m \left\{ \pi_{1B}(s_B) - \pi_{1D}(s_D) + \int_{sD}^{sB} [\partial\pi_{1B}(s)/\partial s]\, ds \right\} > 0,$$

where $\pi_{1B}(s) = \pi_1(\Delta^*(s),s)$, $\Delta^*(s)=c(s,1)-c(s,0)$, and the inequality follows from:

$$\pi_{1B}(s_B) - \pi_{1D}(s_D) = 2t \left\{ \theta_m(\Delta^*(s_D))^2-\theta_m(0)^2 \right\} > 0,$$

$s_B\geq s_C$ (monotone standards) and $\partial\pi_{1B}(s)/\partial s\geq 0$. Finally,

$$R_1-R_2 = \beta_m \left\{ [\pi_{1B}(s_C) - \pi_{2C}(s_C)] - [\pi_{1D}(s_D) - \pi_{2D}(s_D)] + \int_{sC}^{sB} [\partial\pi_{1B}(s)/\partial s]\, ds \right\} > 0,$$

where the inequality follows from $s_B\geq s_C$, $\partial\pi_{1B}(s)/\partial s\geq 0$, and

$$[\pi_{1B}(s_C) - \pi_{2C}(s_C)] - [\pi_{1D}(s_D) - \pi_{2D}(s_D)] = 4tz(2\theta_m(0)-1) > 0,$$

with $z\equiv-\Delta^*(s_C)/6t>0$ and $2\theta_m(0)>1$ (with K>0). QED.

Proof of Proposition 9. Substituting from the first order conditions defining I*(), problem (17) yields the following optimality conditions:

(A15) $\quad s_B$: $q'(I)\, [\partial I^*/\partial s_B]\, X + q(I)[\partial W_B^D /\partial s_B] + \lambda = 0,$

(A16) $\quad s_D$: $q'(I)\, [\partial I^*/\partial s_D]\, X + (1-q(I))[\partial W_D^D/\partial s_D] - \lambda = 0,$

where $\partial I^*/\partial s_B \overset{s}{=} \partial\pi_{1B}/\partial s_B > 0$, $\partial I^*/\partial s_D \overset{s}{=} -\partial\pi_{1D}/\partial s_D > 0$, λ is the non-negative multiplier for the second constraint in (17), and

(A17) $$X \equiv [W_B^D - \beta_m\pi_{1B}] - [W_D^D - \beta_m\pi_{1D}] = \{[W_B^D - \pi_{1B}] - [W_D^D - \pi_{1D}]\} + (1-\beta_m)(\pi_{1B} - \pi_{1D}).$$

Note that with $\beta_m \leq 1$, $s_B \geq s_D$ (by constraint) and $\partial\pi_{1B}/\partial s_B \geq 0$, the last term in (A17) is non-negative. The proof of Proposition 6 establishes that, for any fixed s_B and s_D, the penultimate bracketed term in (A17) is positive. Hence, we have X>0 in the optimum.

Now suppose the second constraint does not bind (λ=0). Then the first terms in (A15)-(A16) are positive (by $q'>0$, $\partial I^*/\partial s_z>0$, and X>0). Hence, in the optimum, $\partial W_z^D/\partial s_z < 0$ (by (A15)-(A16)) and, by concavity of W_z^D and the definition of the ex-post optimum s_z^D (where $\partial W_z^D/\partial s_z=0$), we have $s_z > s_z^D$ in the solution to problem (17).

Suppose instead that the second constraint binds (λ>0). Then by the same argument, we have $s_B > s_B^D$ (from (A15)). Hence, if the proposition is false, we must have $s_D < s_D^D$. However, we then have: $s_D < s_D^D < s_B^D < s_B$, where the penultimate inequality is due to Proposition 3. This inequality contradicts the premise that the second constraint binds. QED.

References

Ambec, S. and P. Barla. "A Theoretical Foundation of the Porter Hypothesis." Economics Letters 75 (2002): 355-60.

Barnett, A.. "The Pigovian Tax Rule Under Monopoly." American Economic Review 70 (1980): 1037-41.

Barrett, S.. "Strategic Environmental Policy and International Trade." J. Public Economics 54 (1994): 325-38.

Biglaiser, G. and J. Horowitz. "Pollution Regulation and Incentives for Pollution-Control Research." J. Economics and Management Strategy 3 (1995): 663-84.

Brander, J. and B. Spencer. "Export Subsidies and International Market Share Rivalry." J. International Economics 18 (1985): 83-100.

Conrad, K.. "Taxes and Subsidies for Pollution-Intensive Industries as a Trade Policy." J. Environmental Economics & Management 25 (1993): 121-35.

Copeland, B.. "Trade and the Environment: Product Standards in a National Treatment Regime." Working Paper, University of British Columbia, January 2001.

Denicolo, V.. "Pollution-Reducing Innovations Under Taxes or Permits." Oxford Economic Papers 51 (1999): 184-99.

Feess, E. and G. Taistra. "Porter's Hypothesis on Environmental Policy in an Oligopoly Model with Cost Asymmetry Caused by Innovation." Jahrbucher for Nationalokonomie und Statistik 220 (2000): 18-31.

Feichtinger, G., R. Hartl, P. Kort, and V. Veliov. "Environmental Policy, the Porter Hypothesis and the Composition of Capital: Effects of Learning and Technological Progress." J. Environmental Economics & Management 50 (2005): 434-46.

Fischer, C., I. Parry and W. Pizer. "Instrument Choice for Envioronmental Protection when Technological Innovation is Endogenous." J. Environmental Economics & Management 45 (2003): 523-45.

Graker, M.. "Strategic Environmental Policy: Eco-Dumping or a Green Strategy?" J. Environmental Economics & Management 45 (2003): 692-707.

Hart, R.. "Growth, Environment and Innovation – A Model with Prouction Vintages and Environmentally Oriented Research." J. Environmental Economics & Management 48 (2004): 1078-98.

Heyes, A. and C. Liston-Heyes. “Corporate Lobbying, Regulatory Conduct and the Porter Hypothesis.” Environmental and Resource Economics 13 (1999): 209-18.

Innes. R. and J. Bial. “Inducing Innovation in the Environmental Technology of Oligopolistic Firms.” J. Industrial Economics 50 (2002): 265-87.

Katsoulacos, Y. and A. Xepapadeas. “Environmental Innovation, Spillovers and Optimal Policy Rules.” In: Environmental Policy and Market Structure, Y. Katsoulacos and A. Xepapadeas, ed.s, Kluwer Academic Publishers, 1996, pp. 143-50.

MacAusland, C.. “Environmental Regulation as Export Promotion: Product Standards for Dirty Intermediate Goods.” Contributions to Economics Analysis & Policy 3 (2004).

Mohr, R.. “Technical Change, External Economies, and the Porter Hypothesis.” J. Environmental Economics & Management 43 (2002): 158-68.

Montero, J.P.. “Permits, Standards and Technology Innovation.” J. Environmental Economics & Management 44 (2002a): 23-44.

Montero, J.P.. “Market Structure and Environmental Innovation.” J. Applied Economics 5 (2002b): 293-325.

Palmer, K., W. Oates and P. Portney. “Tightening Environmental Standards: the Benefit-Cost or the No-Cost Paradigm? J. Economic Perspectives 9 (1995): 119-32.

Parry, I.. “Optimal Pollution Taxes and Endogenous Technological Progress.” Resource and Energy Economics 17 (1995): 69-85.

Popp, D.. “Uncertain R&D and the Porter Hypothesis.” Contributions to Economic Analysis & Policy 4 (2005).

Porter, M.E.. The Competitive Advantage of Nations, MacMillan: London, 1990.

Porter, M.E.. “America’s Green Strategy.” Scientific American 264 (April, 1991): 168.

Porter, M.E. and C. van der Linde. “Toward a New Conception of the Environment-Competitiveness Relationship.” J. Economic Perspectives 9 (1995): 97-118.

Requate, T.. “Dynamic Incentives by Environmental Policy Instruments – A Survey.” Ecological Economics 54 (2005a): 175-95.

Requate, T.. “Timing and Commitment of Environmental Policy, Adoption of New Technology, and Repercussions on R&D.” Environmental & Resource Economics 31 (2005b): 175-99.

Simpson, D. and R. Bradford. "Taxing Variable Cost: Environmental Regulation as Industrial Policy." J. Environmental Economics & Management 30 (1996): 282-300.

Ulph, A.. "Environmental Policy and International Trade when Governments and Producers Act Strategically." J. Environmental Economics & Management 30 (1996): 265-81.

Xepapadeas, A. and A. de Zeeuw. "Environmental Policy and Competitiveness: The Porter Hypothesis and the Composition of Capital." J. Environmental Economics & Management 37 (1999): 165-82.

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 When Standards Do Not Decrease with Technology Improvement

	State z	s_z	θ_z	π_{1z}	π_{2z}	W_z^D	W_z^G
1) Ex-Ante Domestic Optimum, Case 1	A	1.247	.555	1.602	0.936	.955	1.891
	B	1.247	.590	1.841	0.758	.896	1.654
	C	1.247	.521	1.379	1.128	.411	1.539
	D	1.147	.555	1.622	0.956	.371	1.326
2) Ex-Ante Domestic Optimum, Case 2	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	.427	0.583	1.167	-.074	1.093
	D	1.080	.500	0.892	0.892	-.111	0.781
3) Ex-Ante Global Optimum, Case 1 [A]	A	0.970	.555	1.658	0.991	.902	1.893
	B	0.970	.582	1.842	0.852	.854	1.706
	C	0.970	.529	1.482	1.139	.477	1.616
	D	0.820	.555	1.688	1.021	.431	1.452

	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-Ante Dom. Opt., Case 1	.547	.429	1.559	0.867	.142	-.071	.053	.029	.600	1.467
2) Ex-Ante Dom. Opt., Case 2	.742	.745	0.768	0.767	.105	-.046	.024	.024	.325	1.093
3) Ex-Ante Global Opt., Case 1	.369	.206	1.658	0.961	.167	-.063	.063	.037	.551	1.512

[A] The monotonicity constraint on standards does not bind in the ex-ante global optimum for case 2 (see Table 1B); hence, the monotonicity constrained optimum is the same as described in Table 1B.

Table 3. Numerical Results with Technology Transfer and Monotonic Standards[A]

	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	1.319	.555		1.588	0.921	.956	1.877
	B	1.319	.592		1.840	0.734	.895	1.629
	C	1.319	.519	x	1.368	1.141	.736	1.506
	D	1.159	.555		1.620	0.953	.367	1.320
2) Ex-Ante Global Optimum, Case 1	A	1.081	.555		1.636	0.969	.932	1.901
	B	1.081	.586		1.841	0.814	.880	1.694
	C	1.081	.525	x	1.455	1.149	.752	1.901
	D	0.901	.555		1.672	1.005	.426	1.431

	q_1	q_2	π_1^*	π_2^*	W^{D*}	W^{G*}
1) Ex-Ante Dom. Opt., Case 1	.546	.467	1.544	0.858	.670	1.528
2) Ex-Ante Global Opt., Case 1	.422	.327	1.619	0.933	.632	1.565

[A]In case 2, the monotonicity constraint on standards ensures that technology does not transfer. Hence, the ex-ante domestic optimum is as described in Table 2 and the ex-ante global optimum is 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 under the "equal splitting rule" for sharing of joint gains from trade.

Table 4. 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	1.358	.555		1.580	0.914	.954	1.868
Domestic	B	1.358	.593	.067	1.840	0.721	1.080	1.801
Optimum,	C	1.358	.518	x	1.354	1.140	.728	1.868
Case 1	D	1.138	.555		1.624	0.957	.374	1.331
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	1.433	1.147	.753	1.900
Case 1	D	0.901	.555		1.669	1.003	.425	1.428
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	.547	.468	1.539	0.853	.724	1.577
2) Ex-Ante Global, Case 1	.438	.344	1.608	0.921	.689	1.611
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 under the "equal splitting rule" for sharing of joint gains from trade. When subsidized transfer occurs, reported welfares account for benefits of technology exchange, less government costs of subsidy.

$^{o}_{C}$ $^{o}_{B}$ $^{F}_{A}$ $^{F}_{B}$ $^{F}_{C}$ $^{F}_{D}$ $^{D}_{A}$ s^{D}_{B} s^{D}_{C} $^{*}_{C}$ $^{F*}_{z}$

δδδδδδδ

$^{*}_{A}$ $^{*}_{B}$ $^{D*}_{A}$ $^{D*}_{B}$ $^{*}_{z}$ $^{D*}_{z}$ $^{D**}_{z}$ $^{o}_{z}$ $^{D**}_{A}$ $^{D**}_{B}$ $^{*}_{s}$ $^{*}_{ss}$ $^{D**}_{C}$ $^{F*}_{A}$ $^{F*}_{C}$

$W^{o\ o\ o\ o}_{A\ B\ C\ D}$

s^{D}_{A} s^{D}_{B} s^{D}_{C} s^{D}_{D} s^{G}_{A} s^{G}_{B} s^{G}_{C} $^{G}_{D}$ W^{D}_{z} s^{D}_{z} s^{G}_{z} $^{F}_{1}$ $^{F}_{2}$ $^{DT}_{B}$ $\overset{s}{=}$

π^{*}_{1} π^{*}_{2} $_{A}\pi_{1}$ π_{1B} π1C π1D π_{2A} π2B π2C π2D I^{**}_{1} $^{**}_{2}$ $^{*}_{1B}$ $^{*}_{s}$

$^{*}_{2B}$

$$\text{(9a)}\quad I_1:\ \max_{I}\ \pi^{*}_{1}(I;I_2) \equiv q(I)q(I_2)\,\pi_{1A} + q(I)(1-q(I_2))\,\pi_{1B} + (1-q(I))q(I_2)\,\pi_{1C}$$

$$+ (1-q(I))(1-q(I_2))\,\pi_{1D} - rI \ \Rightarrow\ I_1 = I^{**}_{1}(s_A, s_B, s_C, s_D; I_2),$$

$$\text{(9b)}\quad I_2:\ \max_{I}\ \pi^{*}_{2}(I;I_1) \equiv q(I)q(I_1)\,\pi_{2A} + q(I)(1-q(I_1))\,\pi_{2C} + (1-q(I))q(I_1)\,\pi_{2B}$$

$$+ (1-q(I))(1-q(I_1))\,\pi_{2D} - rI \ \Rightarrow\ I_2 = I^{**}_{2}(s_A, s_B, s_C, s_D; I_1),$$

For example, we can show:

Observation. Let us suppose that fixed costs are linear in standards, F(s)=fs with f>0, $d\pi_{1B}/ds_B \geq 0$ at $s_B = s^D_B$, $s^D_A \geq s^D_B$, and $d\pi_{2C}/ds_C \geq 0$ at $s_C = s^D_C$. Then at the ex-post optimum (s^D_A. s^D_B, s^D_C, s^D_D), equilibrium marginal effects of standards on R&D by the foreign firm satisfy: $dI^{*}_{2}/ds_A<0$, $dI^{*}_{2}/ds_B>0$, $dI^{*}_{2}/ds_C>0$, and $dI^{*}_{2}/ds_D>0$.

Proof of Observation. Totally differentiating first order conditions for problems (9a)-(9b) (and appealing to second order conditions) gives:

(A13) $dI_2^{**}/ds_z \overset{s}{=} \{-(\partial^2\pi_1^*/\partial I_1{}^2)(\partial^2\pi_2^*/\partial I_2\partial s_z\} + \{(\partial^2\pi_1^*/\partial I_1\partial s_z)(\partial^2\pi_2^*/\partial I_2\partial I_1)\}$

where

(A14a) $\partial^2\pi_2^*/\partial I_2\partial s_z \overset{s}{=} dI_1^{**}/ds_z$ (per eq. (14)),

(A14b) $\partial^2\pi_2^*/\partial I_2\partial s_A \overset{s}{=} \partial\pi_{2A}/\partial s_A \leq 0$ (<0 when $F'>0$)

(A14c) $\partial^2\pi_2^*/\partial I_2\partial s_B \overset{s}{=} -\partial\pi_{2B}/\partial s_B > 0$

(A14d) $\partial^2\pi_2^*/\partial I_2\partial s_C \overset{s}{=} \partial\pi_{2C}/\partial s_C$

(A14e) $\partial^2\pi_2^*/\partial I_2\partial s_C \overset{s}{=} \partial\pi_{2D}/\partial s_D \geq 0$ (>0 when $F'>0$)

(A14f) $\partial^2\pi_2^*/\partial I_2\partial I_1 \overset{s}{=} [\pi_{2A}+\pi_{2D}] - [\pi_{2B}+\pi_{2C}]$.

To derive the claimed comparative statics at the ex-post optimum under the assumed conditions (with $F'>0$, $\partial\pi_{1B}/\partial s_B \geq 0$, and $\partial\pi_{2C}/\partial s_C \geq 0$), second order conditions ($\partial^2\pi_1^*/\partial I_1{}^2<0$), eq. (14) and (A13)-(A14) imply that the following will suffice: $\partial^2\pi_2^*/\partial I_2\partial I_1 \geq 0$. To establish this inequality, we expand the right hand side of (A14f) evaluated at ex-post optimal standards:

(A15) $[\pi_{2A}+\pi_{2D}] - [\pi_{2B}+\pi_{2C}] > 2t\{[2(1-\theta_m(0))^2 - (1-\theta_m(-\Delta_C))^2 - (1-\theta_m(\Delta_C))^2]$

$+ [(1-\theta_m(-\Delta_C))^2 - (1-\theta_m(\Delta_B))^2]\}$

$= (1/3)\{(-\Delta_C{}^2/3t) + (\Delta_C-\Delta_B)[(1-\theta_m(\Delta_B))+(1-\theta_m(\Delta_C))]\}$

$> (1/3)\{(-\Delta_C{}^2/3t)+2\Delta_C(1-\theta_m(\Delta_C))\} = (2\Delta_C/3)((1-\theta_m(0))) > 0$,

where: (i) the first inequality is due to $s_B^D + s_C^D > s_A^D + s_D^D$ when $s_A^D \geq s_B^D$ (Proposition 4) and $f>0$; (ii) the next equality substitutes for $1-\theta_m(\Delta)=[t+((\Delta-K)/3)]/2t$ in the second bracketed difference and, in the first bracketed difference,

$$(1-\theta_m(-\Delta_C))^2+(1-\theta_m(\Delta_C))^2 = 2(1-\theta_m(0))^2 + \int_0^{dc} (d/d\Delta)[\,(1-\theta_m(-\Delta))^2 +(1-\theta_m(\Delta))^2]d\Delta$$

$$= 2(1-\theta_m(0))^2 + (1/9t^2) \int_0^{dc} \Delta\, d\Delta;$$

i. Unfettered Private Technology Transfer with Unconstrained Government 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 in Case 1, we will suppose that joint profit gains from technology transfer are split equally between the two firms. [17] Table 3 describes the associated (Case 1) ex-ante domestic optimum. Perhaps not surprisingly, the government designs its standard so as to elicit technology transfer whenever R&D outcomes are asymmetric. In state B, it encourages both R&D and technology transfer by setting a particularly high standard; [18] because the state B standard is never actually implemented (due to technology transfer), this can be done without cost dot domestic welfare. Note also that the state A standard is very close to its ex-post optimal counterpart. The reason is that, with technology transfer in states B and C, state A arises with very high probability (91.4 percent); hence, innovation and transfer incentives are best achieved with distortions in the other standards. Finally, we observe that the ability to elicit the transfer of technology enables relatively large improvements in expected social welfare.

[17] For example, 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: $\pi^*_{1B} = \pi_{1B}+(G_B/2)$, $\pi^*_{2B} = \pi_{2B}+(G_B/2)$.

[18] In searching for the optimum of Table 3, standards are allowed to vary to levels that make firm 2 production unprofitable. In such cases, firm 2 does not operate (with $\theta_m=1$) and firm 1's pricing choice and attendant profit are the outcome of a profit maximization constrained by a zero-profit condition for firm 2.

Table 3. Numerical Results with Technology Transfer, Case 1[A]

	State z	s_z	θ_z	π_{1z}	π_{2z}	W_z^D	W_z^G
Ex-Ante Domestic Optimum, Case 1	A	1.262	.555	1.599	0.933	.955	1.888
	B	3.574	.655	2.195[B]	0.337[B]	1.551[B]	1.888[B]
	C	1.190	.522	1.401[B]	1.131[B]	.757[B]	1.888[B]
	D	0.722	.555	1.707	1.041	.428	1.469

	q_1	q_2	π_1^*	π_2^*	W^{D*}	W^{G*}
Ex-Ante Dom. Opt., Case 1	.628	.755	1.546	0.766	.844	1.610

[A] No monotonicity constraint is imposed on standards in the optimization presented in this Table.
[B] Technology transfer occurs in states B and C. Profits reported for these states account for benefits of technology sale under the "equal splitting rule" for sharing of joint gains from trade.