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Olivier Cadot
Bernard Sinclair-Desgagné

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Innovation Under the Threat of Stricter Environmental Standards[*]

Olivier Cadot[†], *Bernard Sinclair-Desgagné*[‡]

Abstract/Résumé

This paper considers the threat of stricter regulation as a policy instrument to enhance innovation into cleaner technology. It is argued that in some contexts the government would find it optimal to regulate with positive probability but not with certainty. In those contexts the optimal policy is indeed made of regulatory threats; furthermore, we show that it is time-consistent, credible, involving little information, and immune to ex post renegotiation.

Ce document considère la menace d'une réglementation environnementale plus stricte en tant qu'instrument de politique économique visant à stimuler l'innovation. Il est démontré que, dans certains cas, le gouvernement préférerait réglementer avec une probabilité positive mais pas avec certitude. Dans ces situations, la politique optimale est en effet constituée de menaces de réglementation; il est de plus démontré qu'elle est cohérente dans le temps, crédible, peu exigeante en rcimonieuse et robuste à la renégociation.

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[†] INSEAD.

[‡] École Polytechnique de Montréal - *Chaire Jarislowsky*, et CIRANO.

1. Introduction

Corrective policies for environmental externalities may take a number of forms. The ones most commonly analyzed in the literature are emission taxes, emission-abatement subsidies, direct regulation through technical standards and tradeable permits [see Baumol and Oates (1988)]. Little attention has been given so far to the *threat* of environmental regulation. In a recent paper, Glazer and McMillan (1992) argue, however, that "Regulation does not always appear as an unexpected event, and threatened firms may alter their behavior in order to reduce the probability of regulation." For example, when German environment minister Klaus Töpfer threatened to force automakers to take back the 2 million cars that are scrapped in Germany each year, Germany's automakers, in particular Volkswagen, ran to establish efficient disassembly systems [Schmidheiny (1992)].[1] This paper therefore examines the transition process towards new environmental standards and the innovation effort of a monopolist threatened by a change of environmental regulation.

There is now a growing literature on the appropriate incentives for environmental innovation.[2] Each policy instrument raises specific problems, but some issues are generic. First, a government attempting to enforce socially desirable norms on private firms is likely to face information-elicitation problems [see Laffont and Tirole (1993) and references therein]. For instance, when firms have private information on the cost of compliance to new regulation and regulators cannot precommit to a future course of action, the well-known "ratchet" effect appears [see, e.g., Weitzman (1980), Freixas, Guesnerie and Tirole (1985), and Rey and Salanié (1990)].[3] Second, environmental regulation affects technology choices, and the question of whether tighter standards can be held responsible for reduced productivity growth has attracted a considerable amount of attention, particularly in the United States. Finally, independently of the information structure, government enforcement of social objectives in the absence of precommitment raises *time-consistency* issues [see Malik (1991)]: if the time of regulatory change is conditioned on the domestic industry's readiness, a perverse incentive is created and foot-dragging may be encour-

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[1] The minister initially set 1993 as the deadline before enforcing tougher rules. This time schedule was not fulfilled, however, which illustrates once more the difficulty of following precise calendars in this area. Below we insist that regulatory policies should be *time-consistent*, i.e. immune to being revised when the deadline comes.

[2] See, e.g., Downing and White (1986), Milliman and Prince (1989), and Carraro and Siniscalco (1991).

[3] Ratcheting refers to a situation that is well-known to prisoners of war. If they work hard initially, they elicit information on their working capabilities which may be used by the camp authorities to increase their future workload. In the absence of precommitment, the equilibrium outcome thus involves suboptimal effort in the first period. Ratcheting has been studied in the context of environmental regulation by Yao (1988).

aged; if, on the other hand, the time of regulatory change is set independently of the industry's state of preparation, a government with industrial policy concerns will want to revise its choices if the industry is not ready when time for change comes. It is on this latter issue that we focus.

We consider the problem of a government facing pressure to adopt stricter pollutant emission standards while polluting firms insist that they need time to develop alternatives to current technologies. The context is one of a small open economy. In a country taking a leading position in setting new environmental standards, the standard-setting process is likely to involve extensive bargaining between producers and government agencies [see Spulber (1989)]. By contrast, in a small (follower) country, foreign standards, especially if they come from a large country, constitute an exogenous reference. The trade-off faced by the government is the following. Simply waiting for the domestic industry to develop its own technology for complying with socially desirable standards is not a solution if developing the technology does not provide privately adequate returns. On the other hand, imposing at once the desired standard may put an excessive burden on the regulated industry. An incentive scheme is required, but if such a scheme takes account, explicitely or implicitely, of the industry's preparation, a perverse incentive is created which ultimately hinders innovation.

There is a close analogy between this problem and the more general one of standards harmonization [see Dean (1991) and Krutilla (1991)]. To some extent adopting foreign environmental standards can also be viewed as a process of trade liberalization. Time-consistency issues are likely to arise in this context and were recently analyzed by Matsuyama (1990). What makes the problem of environmental regulation distinct and interesting, however, is that it combines these issues with issues of incentives for innovation.

The conflicts and trade-offs that we point at above are studied here within the framework of an infinite-horizon game of perfect information between the government and domestic industry, represented by a single firm. The game is stochastic, as the firm's innovation effort is subject to uncertain success. In a game, the incentive scheme that we seek to derive takes the form of an equilibrium (i.e. *time consistent*) strategy profile. We impose three additional requirements on this incentive scheme: that it should not involve non-credible threats — i.e. be *subgame perfect*, that it should be robust to collective deviations — i.e. be *renegotiation-proof*, and that it should be *simple* in terms of informational and memory requirements.

We show that an incentive scheme satisfying simultaneously all these requirements can be implemented as the only perfect Markov equilibrium of the game. Regulatory uncertainty emerges as an incentive device that the government uses to induce the domestic firm to invest in the development of new technology. The probability of regulation decreases over time, however, as the firm successfully completes intermediate stages of the technology-development process. Therefore the outcome is characterized by an *escalating commitment* of the government in favor of the firm's development effort. In addition, as the private return of the technology development project increases, the probability of regulation goes down, i.e. the incentive scheme becomes softer, and the probability of completion increases. Therefore, the inefficiency associated with a positive probability of regulation is reduce for (privately) better projects. Finally, as the government's preference for immediate regulation — a proxy for environmentalist pressure — increases, the firm's probability of development goes up. But as the government's preference for successful development of a domestic technology — a proxy for industrial-policy concerns — increases, the firm's probability of development goes down. In other words, governments that care too much too openly about domestic competitiveness are taken hostage.

The paper is organized as follows. The model is presented in section 2. Section 3 presents the main results. Section 4 contains some concluding remarks.

2. The Model

One stage of the game in extensive form is depicted in figure 1. The players are the government and a domestic firm. At the beginning of each period, the government moves first by choosing to enact (r) or to delay ($\bar{r}$) a strict standard concerning the emission of pollutants. If the government regulates, the game ends[4]; if it does not, the firm's node is reached. The firm may pursue (d) or not pursue ($\bar{d}$) the development of its own cleaner technology[5]. If it chooses not to develop the technology, one period elapses and the game starts again. If it chooses to develop, a chance node is reached, as success in developing the new technology is uncertain. Whatever happens, one period elapses. If the firm is lucky, the game jumps to a new state with lower emissions. If it is not, the game starts all over again.

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[4] The reason is that if the government regulates, the domestic firm has no option but to adopt an existing foreign technology through a licensing agreement. This implies strategic choices for the domestic firm which preclude simultaneously pursuing the development of its own technology.

[5] The assumption of fixed intensity of R&D effort is also used by Fudenberg, Gilbert, Stiglitz and Tirole (1983) and by Choi (1991).

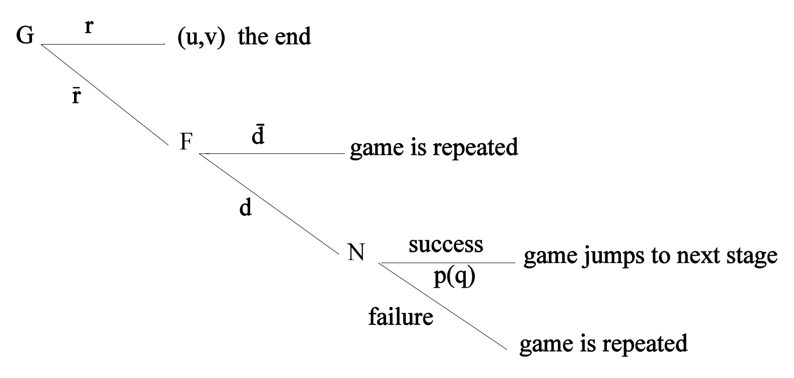

Figure 1. The stage game.

Reducing emissions e to the level compatible with the strict standard takes two stages: the firm must first go from an initial state of high emissions (e = h) through a medium yet unsatisfactory level (e = m) before reaching the low, appropriate level ($e = \ell$). The probabilities p and q governing transitions of the emission process $\{e_t\}$ generate the following Markov matrix:

$$\begin{bmatrix} 1\text{-}p & p & 0 \\ 0 & 1\text{-}q & q \\ 0 & 0 & 1 \end{bmatrix}$$

When state ℓ is reached, the game ends after a trivial move by the government consisting of regulating.[6]

Until the firm has reached state ℓ and unless the government has introduced the new regulation, the firm and the government receive instantaneous payoffs normalized to zero. The firm incurs flow costs of K in state *h* and k in state *m* in each

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[6] Stochastic models of innovation with multi-stage development processes have been studied by Grossman and Shapiro (1987) and Harris and Vickers (1987) among others. Both papers study R&D races between two firms and allow for variable R&D intensities. We consider here the simple case where there is only one home firm capable of developing the alternative technology, as in Grossman and Shapiro (1986).

period where it decides to pursue the development of the cleaner technology. Let's assume that the government and the firm share the same discount factor $\delta = 1/(1+r)$.

If the government regulates before the new technology development is completed, the government and the firm receive $\bar{v}$ and $\bar{u}$ respectively. If state ℓ is achieved, the government and the firm receive respective payoffs v^* and u^* (discounted by one period, since the firm moves last).

The firm's and government's respective preferences over payoffs are represented by the following inequalities:

$$\begin{aligned} \bar{u} &< 0 < u^* \\ 0 &< \bar{v} < v^* \end{aligned} \tag{2}$$

The firm's first inequality means that early regulation, before its own technology is developed, is the worst of all outcomes; the second inequality means that an outcome where new standards are imposed when the firm has succeeded is best and is in particular better than the status quo, for it gives the domestic firm a leadership position in the new technology. The government's first inequality implies that forcing regulation on the unprepared firm is better than the status quo; the second inequality says that the government internalizes the firm's objectives to some extent, by putting a premium on having the firm prepared.

In general, a strategy for either player is a sequence of functions mapping game histories up to any time t into a number in the interval [0,1]. This number is, for the firm, the probability that it develops the cleaner technology, and for the government, the probability of enacting the strict standards. Now, a *Markov* strategy for either player is a function mapping the state space $E = \{h, m, \ell\}$ into the interval [0,1]. That is, such a strategy conditions *only* on the current state e_t of the development process (instead of conditioning on the whole game history) and must specify identical moves for periods where the process is in the same state[7]. We will denote by X the probability that the government regulates when the state is h, and by x the probability that it regulates when the state is m. Similarly, we denote by Y the probability that the firm develops when the state is h, and by y the probability that it develops when the state is m. X, x, Y and y will be either zero or one for pure strategies. As a last piece of notation, the "regulate" and "don't regulate" moves are

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[7] See Maskin and Tirole (1989) and Fudenberg and Tirole (1991) for formal definitions, examples, and references. Markov strategies are plausible in the present context, because failure does not carry any information on the chances of success. If the parameters of the development process were to be learnt over time, as in a "bandit" problem, restricting the strategy space to Markov strategies would be more problematic.

labeled R and $\bar{R}$ respectively in state h, and r and $\bar{r}$ in state m; and the “develop” and “don’t develop” moves are labeled D and $\bar{D}$ in state h and d and $\bar{d}$ in state m.

3. Results

We shall focus on Markov strategies. This ensures that any equilibrium will involve *simple* action rules. As the government moves first in each period, it cannot condition on the firm’s effort choice in the current period; the Markov assumption also implies that it will not condition on the firm’s choice of effort in past periods. Hence, the government’s strategy involves a *minimal amount of memory*.

If one solves the game using dynamic programming, the Markov restriction also simplifies the work. Because history does not matter, payoffs which otherwise would have to be written in full over the infinite horizon take on a simple recursive structure. It can be shown that there is a *unique* Markov perfect equilibrium for each given set of parameters.[8]

In state *m*, the set of parameters can be partitioned into three regions.

◦ Let *region* φ be the one where parameters satisfy:

$$0 < k \leq \delta q u^* .$$

In this region there is a the unique equilibrium ($\bar{r}$,d), in pure strategies: the government does not regulate and the firm expends effort into developing the technology. The cost of development *k* is sufficiently low for the firm to develop without any incentive from the government.

◦ Let *region* χ be defined by the inequalities:

$$\delta q u^* < k < \delta q(u^* - \bar{u}) .$$

Private development costs *k* are higher in this region and an incentive is needed. This incentive takes the form of a threat to impose stricter pollution standards. At equilibrium the government threatens to regulate with a probability that is just sufficient to induce the firm to expend development efforts with positive frequency. The government’s probability of “surprise” regulation creates, for the firm, an incentive to get out of the current state *m* into the safe state ℓ. The only way to do this is to put in effort to develop the new technology.

In this mixed-strategy equilibrium, the two randomized strategies support each other in the usual way. Given the government’s probability of regulating, the

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[8] Rigorous derivation of this result and of many others contained in this section is easy but tedious. Proofs are therefore omitted. The interested reader is of course welcome to get a copy of them from the authors.

firm is just indifferent between developing and not developing its technology. It, in turn, picks the probability of developing that makes the government just indifferent between regulating and not regulating.

Randomization devices are common in enforcement situations. For instance, auditing frequencies, whether by tax authorities, customs, or firm headquarters, are designed in such a way as to appear random to the auditees. Of course, everyone could be audited everyday, but this would be prohibitively costly. Similar reasoning applies here. Regulating has a cost to the government: the difference between the equilibrium payoff and $\bar{v}$. Therefore the government wants to apply only "necessary force".

- Finally, let *region* ψ be characterized by

$$\delta q(u^* - \bar{u}) \leq k \,.$$

In this region the cost of development *k* is too high. The only equilibrium is in pure strategies - $(r,\bar{d})$ - and it has the firm not developing and the government regulating.

There are three similar parameter regions in state *h*, determined by the relative size of the first-period development cost *K*. Let us call these regions Φ, X, Ψ respectively. Combining the corresponding restrictions on the parameters with those defining the regions in state *m* yields the nine scenarios which are displayed in table 1.

Regions in state h // ***Regions in state m***

	ϕ: $0 \leq k \leq \delta q u^*$	χ: $\delta q u^* < k < \delta q(u^* - \bar{u})$	ψ: $\delta q(u^* - \bar{u}) \leq k$
Φ: $0 \leq K \leq \delta p u$	firm always tries to innovate	inconsistent case	government
X: $\delta p u < K < \delta p(u - \bar{u})$	*regulatory threat in state h only; firm always tries to innovate in state m*	*persistent regulatory threat that becomes weaker in state m*	regulates
Ψ: $\delta p(u - \bar{u}) \leq K$	government	regulates	right away

Table 1. Scenarios.

Some scenarios are internally inconsistent and can therefore be disposed of; some others imply trivial outcomes. First, region Ψ (and scenarios $\Psi\varphi$, $\Psi\chi$, $\Psi\psi$) corresponds to the noninteresting case where the government regulates right away, at the start of the game. In region ψ, the government regulates for sure as soon as the game reaches state m. Scenarios $\boldsymbol{\Phi}\psi$ and $\mathbf{X}\psi$ then produce also a trivial outcome. Since the government must regulate when state m is reached and interim payoffs are 0, why wait? The government has to regulate immediately in state h. Another trivial case is the one implicit in scenario $\boldsymbol{\Phi}\varphi$. Here, the government never needs to regulate, for the firm always attempts to develop its technology. Scenario $\boldsymbol{\Phi}\chi$, finally, is inconsistent. It can be shown that there exists no pair of costs (K,k) satisfying all the inequalities that define this region.[9]

We are therefore left with two interesting scenarios: $\mathbf{X}\varphi$ and $\mathbf{X}\chi$. Under both of these scenarios, equilibrium strategies in state h are probabilities (mixed strategies).

◦ In *scenario* $\boldsymbol{X\varphi}$, the private return to the development project becomes positive after a first success. The structure of the incentive scheme is then that the government commits implicitely, in state m, to wait as long as necessary for the firm to bring its new technology to state ℓ. This is what drives the firm's incentive to put in the effort in state h. Because in state h, the threat of surprise regulation is looming, the firm tries to get into the safe state m. Note that the regulatory process can be "captured" by the firm in the sense that it may take an arbitrarily long time to get to state ℓ. This is not a moral hazard problem, however, since it appears only in a state where the private return to the project has turned positive.

◦ In *scenario* $\boldsymbol{X\chi}$, the private return to technology development is still negative in state m. The firm then always needs to be pushed in the back. The incentive scheme takes the form of a threat (probability) to regulate that becomes softer (lower) after a first success. Accordingly, the firm expends effort with a higher frequency when state m is reached.

This result — escalating commitment towards the domestic technology — can be generalized to more than two states. What it means is that even if the private return is negative at the project's ultimate stage, the incentive needed for a given level of effort becomes weaker after each transition. This is a direct consequence of the fact that the value of the dynamic program is increasing with each successful transition. Stated differently, the probability of regulation conditional on no regulation having taken place — the discrete-time equivalent of a hazard rate — is decreasing in steps[10].

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[9] A proof of this can be obtained from the authors on request.

[10] A qualitatively similar result would be obtained in a game of incomplete information with two types of government, a tough one with a high probability of regulation and a soft one with a low probability of regulation. The firm would then update downward its prior about the probability of regulation with each period where regulation does not take place. The main difference is that the time path of the probability of regulation would be smooth rather than decreasing in discrete steps.

3.1 Comparative statics

Comparative statics can now be performed in the relevant regions. This helps understand the intuition of the equilibrium as well as its predictive power.

◦ First, if the private value of the technology development project increases, i.e. either *k*, *q* or u^* increase, then the incentive scheme becomes softer. Let $\Delta = k + q\bar{u} - \delta q u^*$, we have that:

$$\frac{\partial x}{\partial k} = -\frac{(1-\delta) q \bar{u}}{\delta \Delta^2} > 0$$

$$\frac{\partial x}{\partial q} = \frac{1-\delta}{\delta \Delta^2}\left[(k + q\bar{u} - \delta q u^*) - (\delta q u^* - k)\bar{u}\right] < 0 \tag{3}$$

$$\frac{\partial x}{\partial u^*} = \frac{(1-\delta) q \bar{u}}{\Delta^2} < 0$$

◦ Second, an increase in the government's industrial-policy preference reduces the firm's effort. Formally, let *y* by the (equilibrium) probability that the firm expends effort on developing its own technology in state *m*, then

$$\frac{\partial y}{\partial v^*} = \frac{-\delta(1-\delta) q \bar{v}}{[\delta q (v^* - \bar{v})]^2} < 0 \tag{4}$$

◦ Last, an increase in the government valuation of immediate regulation increases the firm's effort. That is:

$$\frac{\partial y}{\partial \bar{v}} = \frac{(1-\delta) v^*}{\delta q (v^* - \bar{v})^2} > 0 \tag{5}$$

The incentive scheme thus behaves in a manner similar to that of a negotiated settlement: when the government's outside opportunities improve through $\bar{v}$ (equation (4)), the settlement tilts in favor of the government, and conversely if its gain from cooperation ($v^* - \bar{v}$) increases (equation (3)). Furthermore, the inefficiency associated with a positive probability of regulation goes down when the project improves in the sense of a higher probability of success, a lower cost of development or a higher final prize (equation (2)).

3.2 Renegotiation

Whenever a repeated-game equilibrium is based on punishments that are costly to the punisher, the question arises as to whether such punishments are renegotiable. Here, the incentive scheme rests on the government's threat of regulation. Suppose that after the suitable randomization, the government draws the "regulate" card. Shouldn't it renegotiate with the firm and start all over again? Note first that, because the equilibrium is in Markov strategies, it satisfies the criterion of *subgame-consistency* [Selten (1973), Selten and Harsanyi(1988)]. This criterion requires that play in subgames that are isomorphic be identical. Here, all subgames played in state i, $i = h,m$, are isomorphic; play in those subgames is necessarily identical when strategies are Markov, which is why payoffs take on a very simple recursive structure. In region $X\chi$, the equilibrium is unique and is therefore trivially renegotiation-proof. In region $X\varphi$, the continuation equilibrium for the subgame played in state *m* dominates all other (non-perfect) equilibria; therefore, there is no credible deviation in the sense of Abreu and Pierce (1989)[11]. Each equilibrium is therefore *renegotiation-proof* in its region.

4. Conclusion

Tradeoffs involving industrial policy, technical change and environmental standards have been relatively unexplored in spite of their importance. We have considered the problem of a government balancing a desire for stricter environmental standards — whether politically motivated or not — against a concern for the competitive position of home firms. One way out of the dilemma is to encourage domestic technological solutions to the environmental problem through an incentive scheme. A government that is not willing to throw subsidies at the problem will want to use the threat of stiff environmental standards as the basic incentive device: that is what we propose. Our approach is to set up a few simple criteria: simplicity, time-consistency, subgame perfection, and renegotiation-proofness, and to find a scheme that fulfills all of them simultaneously. Time-consistency (on the equilibrium path) suggests that the scheme should be derived as the Nash equilibrium of an appropriate noncooperative game. Simplicity in turn suggests the use of a well-known restriction on strategies: that they be Markov, i.e. memoryless. Subgame-perfection requires that the government would not use non-credible threats; i.e., that the strategies be time-consistent *off* the equilibrium path. Finally, renegotiation-proofness requires that the

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[11] One could possibly construct supergame equilibria using closed-loop strategies, in the spirit of the Folk theorem. However, such equilibria would impose additional informational requirements on the game — for instance, that the government observes whether or not the firm actually puts in the development effort.

scheme could not be renegotiated by the government and the domestic firm to avoid threats being carried out.

The scheme that we derive takes the form of probabilities of regulation that decrease over time, as the firm successfully completes intermediate stages of the technology-development process. The value of the firm's dynamic program is increasing over time in steps; if and when that value turns positive, the government commits not to regulate until the firm successfully completes the final stage. Therefore the outcome is characterized by regulatory uncertainty and by an escalating commitment of the government in favor of the firm's development effort. The escalating commitment should not be seen in terms of financial resources, but rather in terms of political support. Note that the use of mixed strategies is not a mere "computational" result. Its intuition is based on the idea that the government's regulatory instrument is *indivisible*; creating uncertainty is a way of dosing it.

The scheme reacts to changes in the parameters in an intuitive way. The threat of regulation diminishes and the probability of completion increases when the private return to developing the domestic technology goes up. The inefficiency due to undesired regulation is then minimal for the best projects. If pressure to regulate at once grows, the firm's probability of development goes up. If the government bows more to industrial lobbies, on the other hand, the firm's probability of development decreases. Hence, governments that care too much too openly about domestic competitiveness are taken hostage, and strong endorsement by the government of a domestic firm's opposition to international harmonization might in fact *contribute* to the failure of key development projects.

References

D. Abreu and D. Pierce, "A perspective on renegotiation in repeated games", mimeo, 1989.

W. Baumol and W. Oates, *The Theory of Environmental Policy*, Cambridge U. Press (1991).

C. Carraro and D. Siniscalco, "Environmental innovation policy and international competition", CEPR discussion paper 525 (1991).

J. P. Choy, "Dynamic R&D competition under 'hazard rate' uncertainty", *Rand Journal of Economics* 22, 596-610 (1991).

J. Dean, "Trade and the Environment: a survey of the literature", mimeo, Johns Hopkins (1991).

P. B. Downing and L. J. White, "Innovation in pollution control", *Journal of Environmental Economics and Management* 13, 18-29 (1986).

X. Freixas, R. Guesnerie, and J. Tirole, "Planning under incomplete information and the ratchet effect", *Review of Economic Studies* 52, 173-191 (1985).

D. Fudenberg, R. Gilbert, J. Stiglitz, J. Tirole, "Preemption, leapfrogging and competition in patent races", *European Economic Review* 22, 3-31 (1983).

D. Fudenberg and J. Tirole, *Game Theory*, Cambridge, Mass., The MIT Press (1991).

A. Glazer and H. Macmillan, "Pricing by the firm under regulatory threat", *Quarterly Journal of Economics* 107, 1089-1099 (1992).

G. Grossman and C. Shapiro, "Optimal dynamic R&D programs", *Rand Journal of Economics* 17, 581-593 (1986).

—— and ——, "Dynamic R&D competition", *Economic Journal* 97, 372-387 (1987).

C. Harris and J. Vickers, "Racing with uncertainty", *Review of Economic Studies* 54, 1-21 (1987).

J. Harsanyi and R. Selten, *A general theory of equilibrium selection in games*, MIT Press (1988).

K. Krutilla, "Environmental regulation in an open economy", *Journal of Environmental Economics and Management* 20, 127-142 (1991).

J.-J. Laffont and J. Tirole, *A Theory of Incentives in Procurement and Regulation*, MIT Press (1993).

A. S. Malik, "Permanent versus interim regulations: a game-theoretic analysis", *Journal of Environmental Economics and Management* 21, 127-139 (1991).

E. Maskin and J. Tirole, “Markov equilibrium”, mimeo, Harvard (1991).

K. Matsuyama, “Perfect equilibrium in a trade liberalization game”, *American Economic Review* 80, 480-492 (1990).

S. R. Milliman and R. Prince, “Firm incentives to promote technological change in pollution control”, *Journal of Environmental Economics and Management* 17, 247-265 (1989).

P. Rey and B. Salanié, “Long-term, short-term, and renegotiation: on the value of commitment in contracting”, *Econometrica* 58, 597-620 (1990).

S. Schmidheiny, *Changing Course*, MIT Press (1992).

R. Selten, “A simple model of imperfect competition where 4 are few and 6 are many”, *International Journal of Game Theory* 3, 141-201 (1973).

D. Spulber, *Regulation and markets*, MIT Press (1989).

M. L. Weitzman, “The ratchet principle and performance incentives”, *Bell Journal of Economics* 11, 302-308 (1980).

D. A. Yao, “Strategic responses to automobile emissions control: A game theoretic analysis”, *Journal of Environmental Economics and Management* 15, 419-438 (1988).