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Ambient Environmental Quality Policies in Stochastic Media

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Abstract

This paper considers the performance of ambient environmental quality and emissions (effluent) policies in settings where the ability of the receiving environmental media to assimilate pollution is stochastic, for instance a river with variable streamflow. Our main findings are: (i) ambient environmental quality policies welfare dominate emission policies for sufficiently damaging pollutants and for pollutants with sufficiently high abatement costs; (ii) emissions policies tend to induce over-investment in abatement equipment relative to the socially optimal resource allocation, while ambient policies tend to induce under-investment; and (iii) emission policies produce superior outcomes for welfare relative to ambient policies when abatement costs are low. This suggests an optimal lifecycle of environmental regulations may exist in which ambient environmental policies are used in early periods when abatement markets are relatively undeveloped, then emission policies are employed in later periods as cost-effective abatement equipment becomes available.

JEL Classification: D62; K32; Q38; Q50

Keywords: Environmental policy; ambient standards;

1 Introduction

Most developed nations impose ambient environmental quality standards on the use of air and water resources. Ambient standards, which set limits on allowable pollution concentrations in environmental media, have been used to regulate water quality in industrialized basins at least since the U.S. Rivers and Harbors Act of 1899 and the German Ruhrverband in 1904 and currently serve as the backbone of U.S. environmental policy for both the Clean Air Act and the Clean Water Act. In the U.S., ambient standards on allowable pollution concentrations are codified at the federal level in the National Ambient Air Quality Standards (NAAQS) for criteria air pollutants, in the Safe Drinking Water Act (SDWA), and in water quality-based limitations in the National Pollutant Discharge Elimination System (NPDES), all of which set upper limits on permissible levels of pollution for a given volume of air or water.* National ambient standards are generally delegated to regional authorities, for instance states, watershed authorities, and local and municipal government, who either monitor ambient pollution concentrations remotely or require polluting entities to submit periodic reports on ambient environmental quality levels to support continued operation of polluting facilities, for instance California's Porter-Cologne Water Quality Control Act requires polluting entities such as municipal wastewater facilities to monitor water quality levels downstream from their operations in

*National Ambient Air Quality Standards (NAAQS) is the U.S. set allowable pollution concentrations for six so-called "criteria pollutants" –Carbon Monoxide (CO), Nitrogen oxides (NO_x), Ozone (O_3), Lead (Pb), Sulfur Dioxide (SO_2), and Particulate matter (PM_{10} and $PM_{2.5}$), and similar regulations on ambient air pollution concentrations exist in the United Kingdom, the European Union, Brazil, China, India, Indonesia, Philippines, Thailand and Japan. Ambient standards typically specify both an acceptable annual mean concentration level for each pollutant and a maximum concentration in a given interval of time. For example, the NAAQS for SO_2 pollution measures regional pollution concentrations at the county level and designates a county to be out of attainment if: (i) its annual mean concentration exceeds 0.03 parts per million (ppm); or (ii) the second-highest 24-hour concentration exceeds 0.14 ppm. For more details on the requirements of the U.S. Clean Air Act, see Lave and Omenn (1981) and Liroff (1986).

order to receive discharge permits for their pollution. Given the historic use and continued prevalence of ambient environmental quality standards, and the importance of “clean” air and water for human and environmental health, it is surprising that ambient environmental quality regulations have received relatively little attention in the economics literature to date. Instead, much of the economics literature considers the related problem of controlling pollution *levels*, which is equivalent to controlling pollution concentrations only in the case of deterministic environmental media. This paper considers the economic performance of ambient standards in more general settings where the ability of the receiving environmental media to assimilate pollution is stochastic, as in the case of pollution released in a river with variable seasonal streamflow.

In general, the ability of a given environmental medium to assimilate pollution is stochastic. In the case of water resources, ambient pollution concentrations, and accordingly the environmental damage resulting from a marginal increment of pollution released into the medium, can vary substantially according to seasonal fluctuations in volume, temperature and turbidity, and, in the case of air resources, ambient pollution concentrations resulting from a given volume of pollution are influenced by prevailing climatic characteristics such as thermal structure, circulation, pressure, and humidity. It is well known, for example, that the worst urban air quality days in mountainous regions such as Los Angeles and Mexico City occur during periods of thermal inversion.

In practice, both emissions-based regulations and ambient environmental quality-based regulations are employed to limit the degradation of air and water resources. The U.S. Clean Air Act Amendments of 1990 implemented an emissions-based cap-and-trade program for Sulfur Dioxide (SO_2), which in principle complements the NAAQS for SO_2 pollution, and most OECD countries

currently impose some form of environmental taxes on coal, gasoline, ozone-depleting substances, water pollutants (measured in effluents of oxidizable matters), and municipal sewage in conjunction with the use of ambient standards. To better understand how these policies operate jointly in an over-arching framework of environmental regulations, in particular when environmental media fail to be “well-mixed” across locations, it is essential to characterize the incentives created by ambient policies in isolation.

How do polluting entities respond to ambient standards on allowable pollution concentrations in stochastic environmental media? What are the relative efficiency properties of emissions-based regulations and ambient-based regulations when pollution concentrations are stochastic? How do the underlying characteristics of the environmental media affect the relative performance of ambient standards and emissions standards? Does the type of pollutant matter in the relative performance of emissions-based policies and ambient-based policies? What incentives exist for investment in abatement equipment when pollution damages are stochastic, and do these incentives differ according to the manner in which pollution standards are delegated to polluting entities?

We frame our observations in a setting where property rights for the environmental resource are complete. One example of such a setting is a polluting firm that deposits waste into a river used for drinking water by downstream consumers. The river is “owned” by a regional authority who stands for the welfare of downstream water consumers and seeks to negotiate for a desirable level of pollution control with the firm. If the volume of receiving water in the river is deterministic, effluent standards and ambient water quality standards are equivalent, and the properties supporting a socially optimal resource allocation reduce to those described by Ronald Coase (1955); however, if the

quantity of receiving water varies continuously according to stochastic inputs of rainfall, the schedule of pollution releases that attains the social optimum must also vary continuously to maintain the equality of marginal abatement cost to state-contingent marginal damages. In the event that complete contracts for state-contingent pollution releases are impractical, a natural consideration for the regulator is to compare the relative efficiency of the outcomes when framing the negotiation with the paper mill in terms of reducing pollution releases, for instance by limiting discharge permits, or in terms of maintaining a permissible level of ambient water quality, for instance by imposing a safe drinking standard as a requirement for operation. The main tradeoff facing the regulator in negotiating these alternative policies is that firm performance is superior under emissions standards, because emissions controls in convex profit functions have the desirable property of stabilizing production levels across states of nature, whereas ambient policies make better use of the stochastic media by matching pollution loads to prevailing environmental conditions, which provides a greater level of consumer protection for a given level of pollution. In essence, framing the negotiation in terms of bargaining for pollution *levels* increases the regulator's traction in achieving pollution reductions, leading (on average) to lower equilibrium pollution concentrations, while framing the negotiation in terms of bargaining for pollution *concentrations* minimizes consumer harm for a given level of pollution emissions.

We examine the relative performance of emissions standards and ambient standards as increasing levels of disturbance are introduced into the environmental media. We show that the optimal emissions policy becomes increasingly stringent as the level of disturbance rises in environmental media, whereas the optimal ambient policy can become more more lax. For sufficiently damaging

pollutants and for sufficiently large disturbance terms in the environmental media, we demonstrate that ambient standards have superior efficiency properties relative to emissions standards.

We extend our main observations to cases in which polluting entities make endogenous investments in abatement technology. In this section, we turn to numerical outcomes for the case of linear marginal abatement cost, linear marginal damages, and a uniform distribution for the environmental disturbance term. While the exogenous investment model on which we base our main analytic results is relevant for a large number of environmental policies that require polluters to install so-called “best available technology” as a minimum regulatory requirement, the natural incentives to invest in abatement equipment without such regulatory standards is important for characterizing the efficiency of the resource allocation across production and abatement markets. We find greater levels of abatement investment to take place under emission standards than under ambient standards, with incentives under emissions standards generally leading to “over-investment” relative to the socially optimal resource allocation.

Our paper is related to the literature on stochastic pollution. The literature on stochastic pollution largely emphasizes the role of pollution uncertainty (Innes; Beavis and Dobbs; Zivin, Just and Zilberman; Wirl and Noll) and abatement shocks (Zhao, 2003), which differs substantively from our focus on uncertain damages resulting from deterministic emissions releases into stochastic environmental media.

The remainder of the paper is structured as follows. In the next section we outline the basic model. In Section III, we characterize the socially optimal resource allocation. The social optimum requires increased production loads in low-damage states of nature and reduced pollution loads in high-damage states

of nature in response to continuous variation in the ability of the receiving environmental medium to assimilate pollution. For the remaining analysis on the relative efficiency properties of emissions-based and ambient quality-based regulations, we confine our attention to cases in which optimal state-contingent policies with continuously adjusting pollution levels are not practical. In Section IV, we characterize the performance of ambient environmental policies that set standards on pollution concentrations in the receiving media, and in Section V we examine the relative economic performance of ambient standards and emissions standards. Section VI concludes with a discussion of policy implications.

2 The Model

Consider a polluting entity, which may be a firm, a community waste-disposal facility, or an association of firms and facilities that deposits pollution into a localized environmental medium. The polluting entity faces opportunity costs for reducing emissions, E , into the environmental medium for any level of emissions below the unregulated emissions level, E_{\max} , and we represent these costs by the abatement cost function $-C(E, I)$, where I is a (potentially exogenous) investment level that reflects the existing abatement technology. We assume that a greater level of investment in abatement equipment reduces both marginal abatement costs and the maximal emission level E_{\max} , i.e. $-C_{EI} < 0$, and $E'_{\max}(I) < 0$, and confine our attention to cases in which the abatement cost function is smoothly increasing and convex; that is, for $E < E_{\max}$, we assume $-C_E > 0$, $C_I < 0$, and $-C_{EI} < 0$. For $E \leq E_{\max}$ we assume $C_{EE} > 0$, $C_{II} > 0$, and $C_{EE}C_{II} - [C_{EI}]^2 > 0$.

Investment in abatement equipment is costly. We denote the total cost of investment by $\Gamma(I)$, which is increasing and convex in I , i.e. $\Gamma'(I) > 0$ and

$$\Gamma''(I) > 0.$$

Emissions create social damage among those who derive services from the environmental medium. The key feature of the model is that the social damage from emissions is generated by *ambient* pollution concentrations, which depend, accordingly, on the interaction between emissions and a potentially large number of stochastic environmental variables. For analytic convenience, we assume it is possible to characterize the environmental medium by a single stochastic variable with a known distribution. For example, the polluting entity may be located along a stretch of river with pristine ambient water quality but a variable level of streamflow that depends on a stochastic rainfall parameter. The social damage from a constant level of emissions then varies inversely with the volume of streamflow in the receiving water, with lower ambient water quality downstream from the polluting entity (and higher damages) during “dry” periods than is the case during “wet” periods.

We represent the stochastic quality of the environmental medium by the random parameter φ and relate the ambient pollution concentration to the level of emissions as $A = \varphi E$. We assume that φ is distributed according to a density function f with compact support $[\varphi_l, \varphi_h]$, where $\varphi_l > 0$, and denote the expected quality of the environmental medium as $\bar{\varphi} = E_\varphi\{\varphi\}$, where E_φ is the expectation operator. Our analysis of continuous states of nature applies to the case of river pollution, where the environmental effect of an effluent release with a given biochemical oxygen demand varies continuously with changes in streamflow, and to the case of air pollution where ambient pollution concentrations decrease monotonically with the atmospheric lapse rate.

We consider social damages of the form $D(A, \delta)$, which depends on the ambient concentration of pollution in the environmental medium, A , and a damage

parameter $\delta > 0$ that represents the toxicity of the pollutant. We assume social damages are increasing and (at least weakly) convex in the ambient pollution level, i.e. $D_A(A, \delta) > 0$ and $D_{AA}(A, \delta) \geq 0$. Moreover we assume that an increase in the damage parameter increases both the damage and the marginal damage from an increment in pollution concentrations, i.e. $D_\delta(A, \delta) > 0$ and $D_{A\delta}(A, \delta) > 0$.

Finally, we assume the third derivatives of the functions $C(\cdot)$ and $D(\cdot)$ are sufficiently small so as to not bias our results. For analytical convenience, we set $C_{EEE}(E, I) = D_{AAA}(A, \delta) = 0$.

Our observations are based on the choice of regulatory target between an emissions target, $E \leq E^r$, and an ambient pollution target, $A \leq A^r$. Both policies are used in practice, for instance cap-and-trade regulations for SO_2 with a level of allowances of E^r and ambient water quality regulations that require polluting entities to submit monitoring reports on the quality of receiving water that ensure pollution concentrations remain beneath a tolerance level of A^r .

We decompose the model into three stages, which are sequenced as follows: (i) an environmental policy stage in which the regulator selects a regulatory target (i.e., an emissions target or an ambient target) and fixes the level of the policy target with a standard; (ii) an investment stage in which the polluting entity responds to the environmental policy by selecting an investment level; and (iii) an abatement stage in which the polluting entity chooses a level of abatement effort to meet the standard. In all cases, the polluting entity is represented as an aggregated unit, which implicitly assumes the standard is efficiently allocated between firms and facilities that comprise the polluting entity, as would be the case for a tradeable emissions standard.

We consider two versions of the model, one with exogenous investment and

one with endogenous investment, and begin by studying the former case in which the investment stage is degenerate. This case accords with a number of cases in which environmental polices combine ambient environmental quality standards with technological standards that mandate the polluting entities install the “best-available control technology” prior to polluting an environmental medium. For both versions of the model, an important feature is that the investment level is fixed at the time the short-run abatement decisions are made. Such would be the case when polluters make infrequent investments in abatement equipment, while environmental medium (and the potential matching of abatement effort to environmental conditions) varies continuously.

3 Exogenous Investment

In many cases, environmental policy is imposed through independent restrictions on pollution levels and technological restrictions. The case of exogenous investment is relevant for environmental policies that institute separate policy controls in the form of technological requirements on polluters, for instance the technology-based standards under the U.S. Clean Water Act that require polluters to install the so-called “best available technology” as a minimum regulatory requirement for a pollution permit.

3.1 The Social Optimum

We assume the social objective is to minimize social cost, SC . Given a particular state φ of the environmental medium, social cost can be written in terms of the emissions level,

$$SC(E, \varphi; I) = C(E; I) + D(\varphi E, \delta) + \Gamma(I), \quad (1)$$

or equivalently in terms of the ambient pollution level,

$$SC(A, \varphi; I) = C\left(\frac{A}{\varphi}; I\right) + D(A, \delta) + \Gamma(I), \quad (2)$$

where $\Gamma(I)$ for the moment represents fixed cost.

At the social optimum, a polluting entity endowed with I units of abatement equipment would observe the state of nature φ and then adjust the abatement effort in correspondence with environmental conditions to minimize social cost in (1), or equivalently in (2). Suppressing the investment term in the abatement cost function for notational convenience, minimizing cost with respect to abatement effort gives the first-order condition

$$-C_E(E) = \varphi D_A(\varphi E, \delta). \quad (3)$$

Condition (3) has the usual interpretation that the marginal abatement cost should equal the state contingent level of marginal damage. The state contingent optimum, which involves a continuous adjustment in emissions levels to environmental realizations, is denoted by $E^*(\varphi, \delta)$. Using the implicit function theorem, it is straightforward to verify that $E(\varphi, \delta)$ is decreasing in both φ and δ . The optimal level of emissions decreases in environmental states associated with higher damages and declines with the toxicity of the pollutant.

The optimal ambient pollution level, $A^*(\varphi, \delta) = \varphi E^*(\varphi, \delta)$, is decreasing in δ ; however, the ambient pollution concentration can either increase or decrease in φ , depending on the elasticity of the marginal abatement cost function. Let $\varepsilon_c = -C_{EE}(E, I)E/C_E(E, I) > 0$ denote the elasticity of the marginal abatement cost function.

Proposition 1. $A^*(\varphi, \delta)$ is increasing (decreasing) in φ when $1 \leq (>) \varepsilon_c$.

In response to a highly damaging state of nature in the environmental medium, for instance unusually low streamflow in the receiving water for the

pollution, the optimal ambient pollution concentration is “cleaner” than in less damaging states whenever the marginal abatement cost function is elastic $1 \leq \varepsilon_c$. The reason is that pollution concentrations rise at a unit rate in emissions, whereas marginal abatement cost rises at less than a unit rate in emissions when the marginal abatement cost function is elastic.

In cases where the polluting entity does not internalize social damages, the first-best allocation can be decentralized by a state-contingent emissions policy. To see this, suppose the regulator can select a tax schedule on emissions, $\tau(\varphi)$, that varies according to realized states of nature φ . Under this regulation, the objective function of the polluting entity in the abatement stage is given by

$$TC(E, \tau(\varphi)) = C(E) + \tau(\varphi)E,$$

which leads to an emission level of $E(\tau(\varphi))$ that solves

$$-C_E(E) = \tau(\varphi). \tag{4}$$

By inspection of (3) and (4), this policy results in the optimal state-contingent abatement levels whenever the tax in each state of nature is set equal to the realized marginal damage; that is, when $\tau(\varphi) = \varphi D_A(\varphi E, \delta)$. Alternatively, ignoring for a moment the practicality of such a policy, the regulator could issue state-contingent, tradable permits in the amount $L(\varphi) = E^*(\varphi, \delta)$, which would imply a competitive permit price of $\sigma(\varphi) = \varphi D_A(\varphi E, \delta)$ in state of nature φ .

Now suppose the environmental media varies continuously in its ability to assimilate pollution. In this case, a continuously variable tax (permit allocation) may not be feasible. We begin, instead, by examining an ambient environmental standard that sets the maximum allowable pollution concentration at $A = \varphi E$. After characterizing this policy, we then discuss how the performance of ambient standards compare with the more familiar class of emissions policies that are

designed to limit E without state-contingent adjustments in property rights.

3.2 Ambient Standards

For a given level of an ambient standard, $A = \varphi E$, one of three outcomes must occur for the abatement choice. For sufficiently large values of A , the standard never binds on the choices of the polluter, and, in this case, the polluter chooses $E = E_{\max}$. For smaller values of A , it is possible that the ambient standard binds on the desired emissions level in states of nature with high pollution damages, but not in states of nature with low pollution damages. In this case there exists a $\hat{\varphi} = \hat{\varphi}(A) \in [\varphi_l, \varphi_h]$ such that for $\varphi \geq \hat{\varphi}$ the polluting entity must choose its emission level subject to $E = A/\varphi$ while for $\varphi < \hat{\varphi}$, it free to pollute at the unregulated pollution level, $E = E_{\max}$. We refer to this case throughout the paper as the (globally) “non-binding case”. Finally, it is possible that A is sufficiently stringent that it binds on the desired emissions level for all $\varphi \in [\varphi_l, \varphi_h]$. For notational convenience we define $\hat{\varphi} = \underline{\varphi}$ for this case, which implies that $\hat{\varphi}'(A) = 1/E_{\max} > 0$ (since by definition $\hat{\varphi}(A)E_{\max} = A$). We refer to this case throughout the paper as the (globally) “binding case”.

Now consider the problem of a regulator who seeks to minimize social cost through the selection of an ambient standard. The regulator’s objective function is given by

$$E_{\varphi}(SC_A(A)) = E_{\varphi > \hat{\varphi}} \left\{ C \left(\frac{A}{\varphi}, I \right) \right\} + D(A, \delta) [1 - F(\hat{\varphi}(A))] + \int_{\varphi_l}^{\hat{\varphi}(A)} D(\varphi E_{\max}, \delta) dF(\varphi) + \Gamma(I), \quad (5)$$

where $\Gamma(I)$, again, is a fixed cost component. The objective function has three terms. The first two terms represent abatement cost and social damages in the binding region ($\varphi \geq \hat{\varphi}$) in which the polluting entity selects the emission level $E = A/\varphi$ to exactly meet the ambient standard of A . The third term

represents social damages from pollution in the non-binding region in which the polluter selects $E = E_{\max}$. The interval over which these damages are expressed collapses to zero as $\hat{\varphi}(A) \rightarrow \underline{\varphi}$.

Suppressing the investment variable in the abatement cost function, the regulator's first-order condition is given by (for a derivation see the appendix).

$$E_{\varphi > \hat{\varphi}} \left\{ -C_E \left(\frac{A}{\varphi} \right) \frac{1}{\varphi} \right\} = D_A(A, \delta) [1 - F(\hat{\varphi}(A))] \quad (6)$$

The result follows from condition (14) below.[†] Condition (6) equates expected marginal abatement cost to the expected marginal damage under the ambient standard. For states of nature in which the ambient standard binds, $1 - F(\hat{\varphi}(A))$, the marginal social damage is constant, $D_A(A, \delta)$, and the ambient standard is selected to equate the expected marginal abatement cost over the binding states with the marginal social damage. Let A^* denote the solution to equation (6).

The second-best optimal outcome differs from the first-best outcome in expression (3) in that, under an ambient pollution standard, a single regulated pollution concentration is chosen to equate marginal social damage with the expected marginal abatement cost, rather than selecting separate ambient pollution concentrations in each state of nature to match state-contingent benefits and costs.

The optimal ambient standard, A^* , in (6) depends critically on the degree of toxicity of the pollutant, δ , and on characteristics of the environmental media, φ . Making use of the implicit function theorem on (6) and the second-order condition for the regulator's problem, it is straightforward to show that the optimal ambient policy satisfies $\partial A^* / \partial \delta < 0$. For more damaging pollutants,

[†]Throughout the remainder of the paper, we assume that the second-order condition is satisfied.

the optimal ambient standard decreases the allowable pollution concentration in the environmental medium. Moreover, as δ rises, the tighter ambient standard now binds more frequently across states of nature, which implies that $\hat{\varphi}$ decreases towards $\underline{\varphi}$. Thus, the ambient standard adjusts smoothly from a regime in which the ambient standard binds only in some states of nature to a regime in which the ambient standard is always binding.

A change in the distribution of the disturbance term in the environmental medium alters the optimal ambient standard as follows:

Proposition 2. *Let F and G be two distributions with possibly different support, where $[\varphi_l(F), \varphi_h(F)]$ and $[\varphi_l(G), \varphi_h(G)]$ denote the support of the corresponding distributions. Let $A^*(F)$ and $A^*(G)$ denote the optimal ambient standards with respect to F and G , respectively. If*

$$\int_{\varphi_l(F)}^{\varphi_h(F)} -C_E\left(\frac{A}{\varphi}\right) \frac{1}{\varphi} dF(\varphi) < \int_{\varphi_l(G)}^{\varphi_h(G)} -C_E\left(\frac{A}{\varphi}\right) \frac{1}{\varphi} dG(\varphi) \quad (7)$$

for all A , then $A^(F) < A^*(G)$.*

Proposition 1 states that the optimal ambient standard is relaxed following a rise in expected marginal abatement cost. To understand the intuition for this result, note that (7) can hold for several reasons. Condition (7) can be met when the support for φ shifts outwards (implying the mean of the distribution has increased), as well as when the expected value of φ is held constant in response to an increase in the spread of the distribution. In the event that the function $-C_E\left(\frac{A}{\varphi}\right) \frac{1}{\varphi}$ is convex and the mean of F and G is the same, then (7) says that G second-order stochastically dominates F . An increase in the dispersion of φ increases expected marginal abatement costs when $-C_E\left(\frac{A}{\varphi}\right) \frac{1}{\varphi}$ is convex, and this induces the regulator to relax the ambient standard to mitigate the increase in expected cost for the polluter.

3.3 Emission Standards

Suppose the regulator instead sets an emission standard, E . In the interesting case of environmental regulations set below the optimal emissions level of polluters, the abatement decision of the polluter involves selecting an emissions level that exactly meets the standard.

The regulator's problem can be written as

$$\min_E \{C(E) + E_\varphi D(\varphi E, \delta)\}.$$

The regulator's first-order condition is

$$-C_E(E) = E_\varphi \{\varphi D_A(\varphi E, \delta)\}, \quad (8)$$

which states that the marginal abatement cost be set equal to the expected marginal damage that arises in the stochastic environmental medium under an emissions cap of E . Condition (8) holds both in the case of exogenous investment and endogenous investment.

Notice that the difference between the outcome in (8) and the first-best outcome in (3) is that, under an emission standard, the production level is selected before the state of nature is revealed and, consequently, is based on the expected state of nature, $\bar{\varphi}$, rather than on the actual realization of φ . Let $E^*(\delta)$ denote the solution to (8) and let $E_\varphi \{SC^L(E^*(\delta), \delta)\}$ denote the expected social cost under the optimal emission standard.

It is well known that this outcome can be obtained equivalently by setting a Pigouvian tax. To see this, notice that the polluter's problem under an emissions tax rate of τ is given by

$$\min_E \{C(E) + \tau E\},$$

which has first order condition $-C_E(E) = \tau$. If the regulator sets the Pigouvian tax according to rule

$$\tau = E_\varphi D(\varphi E^*, \delta)$$

then the polluter will choose $E = E^*$, and the result is the same as under an emission standard.

The environmental medium influences the optimal emissions standard as follows:

Proposition 3. *Let F and G be two distributions with possibly different support, where $[\underline{\varphi}(F), \overline{\varphi}(F)]$ and $[\underline{\varphi}(G), \overline{\varphi}(G)]$ denote the support of the corresponding distributions. Let $E^*(F)$ and $E^*(G)$ denote the optimal emission standards with respect to F and G , respectively. If*

$$\int_{\varphi_l(F)}^{\varphi_h(F)} \varphi D_A(\varphi E, \delta) dF(\varphi) < \int_{\varphi_l(G)}^{\varphi_h(G)} \varphi D_A(\varphi E, \delta) dG(\varphi) \quad (9)$$

for all E , then $E^*(F) > E^*(G)$.

Proposition 3 states that if the expected marginal damage under F is smaller than the expected marginal damage under G , the optimal emissions standard becomes more stringent. Notice that condition (9) can hold for several reasons: The support has shifted outwards (implying the mean of the distribution has increased), or the mean is kept constant while the degree of dispersion in the environmental medium has changed. It is straightforward to show that the function $\varphi D_A(\varphi E, \delta)$ is convex in φ . Hence, for equal means of the distributions F and G , condition (9) says that G second-order stochastically dominates F . Greater dispersion in the distribution of φ increases the expected damage of emissions, which is a convex function of pollution concentrations in the environmental medium, and this causes the regulator to set a tighter emission standard.

3.4 Policy Comparison

It is useful to draw some general implications for the policy comparison.

Proposition 4. *Consider the case of exogenous investment in abatement technology (e.g., under a technology standard).*

- i) *For δ sufficiently large, the optimal ambient standard welfare-dominates the optimal emissions standard;*
- ii) *If marginal damage is constant, there exists an interval of damage parameters $[\underline{\delta}, \bar{\delta}]$ and an interval of parameters $[\varphi_l, \varphi_h]$ such that $SC^{\bar{E}}(\bar{E}^*(\delta), \delta) < SC^A(A(\delta), \delta)$ for $\delta \in [\underline{\delta}, \bar{\delta}]$.*

Proof See the appendix.

The intuition for Proposition 4 is that, for a given interval $[\varphi_l, \varphi_h]$, the variability of the damage increases as δ rises. Therefore, fixing the ambient pollution level leads to a lower expected damage. Because the variability in abatement cost for polluting entities depends only on φ , and not on the degree of toxicity of the pollutant, there must be some level of toxicity for which policies targeted to control damages outperform policies designed to control emissions. In contrast, for sufficiently low values of δ , the environmental consequence of increasing the pollution concentration is “small”, and both optimal emission standards and optimal ambient standards are accordingly lax. Because the abatement cost function is convex in φ , policies that limit the variability in cost across states of nature perform better than policies that limit the variability in damages.

3.5 Numerical Examples

The following numerical examples reveal the underpinnings of Proposition 4. In particular, we show that if the volatility of the environmental damage is sufficiently high, ambient emission standards welfare dominate emission standards. For this purpose we specify the abatement cost function as $C(E) = (B - \alpha E)^2 / 2\alpha$, and the damage function alternatively as $D(A) = \delta A$ or $D(A) = \delta A^2 / 2$ to demonstrate the robustness of this conclusion for the case of constant or increasing marginal damage. For the density function, we specify a uniform distribution to characterize the states of nature in the environmental medium, with $f(\varphi) = 1 / (\varphi_h - \varphi_l)$.

Example 1: [`mathfile:Continuous-without-K-CMD1a-new.nb`] Figure 1a depicts the welfare outcomes under an ambient standard (wide dashes), an emission standard (narrow dashes), and for the social optimum (dotted line) with parameters set at $B = 10$, $\alpha = 1$, $\varphi_l = 1$, $\varphi_h = 3$ in the case of damages given by $D(A) = \delta A$ and variation in pollution toxicity in the range $\delta \in [1.0, 3.5]$.

Notice that the emission standard welfare dominates the ambient standard for low values of the damage parameter δ , while the ambient standard performs better for more toxic pollutants. Figure 1b displays the ambient pollution level under ambient standard (wide dashes), and the expected ambient pollution levels for the emission standard (narrow dashes), and for the social optimum (dotted line). We observe that the expected ambient pollution is higher than the expected first-best ambient pollution. The intuition is that since the emission standard is not flexible, it must not be too strict because otherwise the cost of abatement is too high. By contrast the ambient emission standard can be higher or lower than both the expected first-best ambient pollution and the expected

ambient pollution under the emission standard.

Under increasing marginal damage, we find similar results. Under both constant and increasing marginal damage it can happen that the ambient standard always welfare dominates the emission standard.

Figures 1 and 2 about here.

4 Endogenous Abatement

In this section we extend to model by allowing for pre-investment prior to the realization of environmental conditions. Such investment decisions are important in shaping efficient allocations of resources between production and abatement activities.

4.1 Social Optimum

Before we turn to the relative performance of environmental policies based on ambient targets and emissions targets in settings with endogenous investment, it is useful to examine the socially optimal allocation of resources for abatement investment. Making use of the social cost equation (1), consider the optimal investment level in the abatement stage. Given a previous investment level of I a social planner would observe the state of nature φ and then adjust the abatement effort to meet condition (3).

In the investment stage, the investment level is chosen prior to the realization of φ , as would be the case when a plant locates along a river with variable seasonal streamflow. Given the solution in the abatement stage, the optimal choice of I is completely characterized by the solution to

$$\min_I \{E_\varphi [C(E^*(\varphi, \delta; I), I) + D(\varphi E, \delta)] + \Gamma(I)\}$$

Making use of the envelope theorem, the first-order condition for the optimal

ex-ante investment level I is given by

$$\Gamma'(I) = E_{\varphi}[-C_I(E^*(\varphi, \delta; I), I)].^{\ddagger} \quad (10)$$

Condition (10) is intuitive. The right-hand side is the return to abatement investment, which is the expected reduction in marginal abatement cost, $E_{\varphi}[-C_I(E^*(\varphi, I), I)]$ following an additional unit of investment. A social planner would set this marginal benefit equal to the marginal cost of investment, $\Gamma'(I)$.

The first-best outcome is given by the simultaneous solution to equations (3) and (10). Let $I^*(\delta)$ and $E^*(\varphi, \delta)$ denote this outcome.

The first-best allocation can again be decentralized by a state-contingent policy. For example, the regulator can select a tax schedule on emissions, $\tau(\varphi) = \varphi D_A(\varphi E, \delta)$, that varies according to realized states of nature φ . Under this regulation, the objective function of the polluting entity in the abatement stage is given by

$$TC(E, I, \tau(\varphi)) = C(E, I) + \tau(\varphi)E,$$

which leads to an emission level of $E(\tau(\varphi), I)$ that solves equation (4).

To see that a state-contingent policy also produces the desirable investment level in the abatement stage, observe that the firm would set

$$\Gamma'(I) = E_{\varphi}[-C_I(E(\tau(\varphi), I), I)] = E_{\varphi}[-C_I(E^*(\varphi, I), I)] \quad (11)$$

which gives us (10).

4.2 Ambient Standards

Now suppose the environmental media varies continuously in its ability to assimilate pollution. In this case, a continuously variable tax, let alone a policy of continuously varying permit allocations, may be impractical. We therefore

[‡]Our assumptions guarantee that also second-order conditions are satisfied. Details are available from authors on request.

begin by examining an ambient environmental standard that sets the maximum allowable pollution concentration at $A = \varphi E$.

4.2.1 The polluter's investment decision

In the investment stage, the polluter will not invest in abatement technology if the ambient standard is never binding. In the more interesting case where the ambient policy binds in at least some states of nature, the polluting entity's problem is

$$\min_I \{E_{\varphi > \hat{\varphi}} \{C(A/\varphi, I)\} + \Gamma(I)\}.$$

where $\hat{\varphi} \geq \underline{\varphi}$ denotes the lower bound of states of the world φ for which the ambient standard is binding. The optimal investment level solves the first-order condition

$$\Gamma'(I) = E_{\varphi > \hat{\varphi}} [-C_I(A/\varphi, I)], \quad (12)$$

The polluting entity equates marginal investment cost with the (conditional) expected decrease in marginal abatement cost resulting from the investment.

For ambient standards that bind in more states of nature, the return to investment increases. To see this, implicitly differentiate (12) with respect to A and I to obtain:

$$\frac{\partial I}{\partial A} = \frac{E_{\varphi > \hat{\varphi}} [-C_{EI}(A/\varphi, I)/\varphi] + C_I(A/\varphi, I)\hat{\varphi}'(A)}{\Gamma''(I) + E_{\varphi > \hat{\varphi}} [-C_{II}(A/\varphi, I)]} < 0, \quad (13)$$

where the inequality follows from our assumptions on the cost functions C and Γ . Stricter (laxer) ambient standards induce greater (smaller) levels of technological investment.

Ambient standards produce an interesting effect on investment incentives. In the case of a binding ambient standard in which A is set within a range where $\hat{\varphi} = \underline{\varphi}$, a more stringent policy cannot effect the states of nature in which the policy is binding, that is $\hat{\varphi}'(A) = 0$, and investment incentives are accordingly

driven only by the reduction of marginal abatement cost. However, in the non-binding case, a stricter A makes it more probable that a state of nature will arise in which A is binding, $\hat{\varphi}'(A) > 0$, and this additional effect makes abatement investment more attractive to the firm.

4.2.2 The optimal long-term ambient standard

Now consider the problem of a regulator who seeks to minimize social cost through the selection of a long-term ambient standard that takes into account polluters' adaptation to the standard through investment decisions. The regulator's objective function, as before, is given by (5).

The objective function has four terms. The first two terms represent abatement cost and social damages in the binding region ($\varphi \geq \hat{\varphi}$) in which the polluting entity selects the emission level $E = A/\varphi$ to exactly meet the ambient standard of A . The third term represents social damages from pollution in the non-binding region in which the polluter selects $E = E_{\max}$. The interval over which these damages are expressed collapses to zero as $\hat{\varphi}(A) \rightarrow \underline{\varphi}$. The final term in the objective function is the cost of abatement investment. The regulator minimizes this function subject to the polluting entity's first stage investment decision described by equation (12).

The regulator's first-order condition is given by (for a derivation see the appendix):

$$E_{\varphi > \hat{\varphi}} \left\{ -C_E \left(\frac{A}{\varphi}, I \right) \frac{1}{\varphi} \right\} = D_A(A, \delta) \cdot [1 - F(\hat{\varphi}(A))] \quad (14)$$

$$+ E'_{\max}(I) I'(A) \int_{\underline{\varphi}}^{\hat{\varphi}(A)} D_A(\varphi E_{\max}, \delta) \varphi dF(\varphi).^{\S}$$

The sum of terms on the right-hand side of condition (14) is the expected marginal damage of pollution, which is decomposed into terms that represent cases

where the standard on A is binding and non-binding, respectively. For states of nature in which the ambient standard binds, given by probability $1 - F(\hat{\varphi}(A))$, the marginal social damage is constant, $D_A(A, \delta)$, whereas marginal social damage in the non-binding case is the product of the change in the unregulated emissions rate in response to a change in A and the state-contingent damages of the resulting pollution level when the standard is attained. Condition (14) equates expected marginal abatement cost to the expected marginal damage under the standard.

Let A^* denote the solution to equation (14). In the special case, where A is in the binding range for all $\varphi \in [\underline{\varphi}, \bar{\varphi}]$, the optimal ambient standard solves:

$$E_{\varphi} \left\{ -C_E \left(\frac{A}{\varphi}, I \right) \frac{1}{\varphi} \right\} = D_A(A, \delta). \quad (15)$$

4.3 Emission Standards

Suppose the regulator instead sets an emission standard, E . In the interesting case of a binding environmental regulation, the abatement decision of the polluter involves selecting an emissions level that exactly meets the (deterministic) standard on emissions. Thus in the investment stage, the polluter seeks to minimize total cost, $\min_I \{C(E, I) + \Gamma(I)\}$, which leads to the first-order condition

$$-C_I(E, I) = \Gamma'(I). \quad (16)$$

This condition states that the reduction in marginal abatement cost following an increment in technology investment is equal to the marginal investment cost.

Now consider the regulator's problem. The regulator's problem can be written as

$$\min_E C(E, I) + \Gamma(I) + E_{\varphi} D(\varphi E, \delta),$$

subject to (16). On substitution of terms, the regulator's first-order condition is given by (8), which holds both in the case of exogenous investment and endogenous investment. Let $E^*(\delta)$ denote the solution to (8) and let $E_\varphi\{SC^L(E^*(\delta), \delta)\}$ denote the expected social cost under the optimal emission standard. Notice that this outcome also can be obtained by setting a Pigouvian tax $\tau = E_\varphi D(\varphi E^*, \delta)$.

4.4 Numerical Examples

To illustrate our results we extend our previous example by choosing $C(E, I) = (B - I - \alpha E)^2/2\alpha$, $\Gamma(I) = \gamma I^2/2$, and the damage function as $D(A) = \delta_1 A + \delta_2 A^2/2$. The damage function allows us to study both constant and linear marginal damage. As before, we consider a uniform density function for the environmental medium.

Example 2: [`mathfile: New-Model1-numerical2a`] Figure 3 depicts the welfare outcomes under an ambient standard (wide dashes), an emission standard (narrow dashes), and for the social optimum (dotted line) with parameters set at $B = 10$, $\alpha = 1$, $\varphi_l = 1$, $\varphi_h = 4$ for variations in pollution toxicity in the range $\delta_2 \in [0, 1.0]$. Notice that the emission standard welfare dominates the ambient standard for low damage parameters, while the ambient standard fares better for high values of δ_2 . Figure 4 shows the pattern of investment, which is characterized by overinvestment under both forms of environmental policies. However, second best-optimal investment under the second-best optimal ambient standard aligns more closely with the first best levels. Notice that over-investment occurs under the second-best optimal emission standard and under-investment occurs under the second-best optimal ambient standard; however, the investment distortion under the ambient standard is smaller than under the emission standard. Figure 5 shows us the ambient pollution levels

under the three regimes. Here we see that the ambient emission level under the ambient standard is very close to the expected first-best ambient emission level, while emissions depart from the social optimum for higher levels of δ in the case of an emissions standard.[¶]

4.5 Policy Comparison

We have established that ambient policies welfare-dominate emissions policies under a wide range of circumstances in the special case of exogenous investment in abatement equipment. With endogenous investment, we cannot show analytically that the ambient standard outperforms the emission standards; however, our numerical results confirm the results in the case of exogenous investment for a wide range of parameter values. Ambient standards tend to perform particularly well when stochastic damages are influenced by environmental media with a wide support over the potential states of nature, for smaller values of the elasticity of marginal abatement cost, and for more toxic pollutants.

5 Conclusion

The goal of this paper has been to characterize the performance of ambient standards in stochastic environmental media and to examine the relative efficiency of ambient policies that limit *pollution concentrations* and effluent/emissions policies that constrain aggregate *pollution levels*.

This paper has considered the welfare ranking of emissions policies and ambient environmental policies under circumstances of both exogenous and endogenous abatement investment. Under conditions of exogenous abatement in-

[¶]Sensitivity analysis with respect to the parameters B , a , γ , φ_l , and φ_h reveals that the choice of B is irrelevant for the distortions; however, lower values of α (smaller values for the elasticity of marginal abatement cost) favor the use of ambient standards over the emission standards, and a larger spread in the interval of environmental realizations $[\varphi_l, \varphi_h]$ favors ambient emission standards.

vestment, emission policies welfare dominate ambient environmental policies for pollutants associated with small environmental damages on the margin, whereas, for more damaging pollutants, ambient environmental policies welfare dominate emission policies.

Under endogenous investment, the relative welfare performance of emission targets and ambient environmental targets depends, in part, on the ability of each policy to stimulate private investment in pollution control equipment.

An important question that remains for future analysis is how best to implement ambient standards in markets with multiple polluters. If there is a single polluter at a given point, such as a firm polluting a given segment of a river, all responsibility for complying with an ambient standard can be given to the firm. If there is more than one polluter, but the number of polluters is small, the regulator could implement an instrument involving collective punishment in the event that the ambient standard is not met. Instruments like these can be a collective tax, as considered by Segerson (1988), or other forms of collective or random punishments as suggested by Xepapadeas (1991).

In the case of environmental media with directional flows, as in the case of river pollution with upstream and downstream pollution sources, there is a cascading effect of pollution in the river, as pollution released by the upstream firm increases pollution concentrations in the environmental medium facing the downstream firm. The effect of this “shift in the support” of the environmental medium for the downstream firm is to create differential ambient standards at upstream locations (more stringent) and downstream locations (less stringent) to account for the externality of upstream pollution on downstream environmental conditions facing the second firm. At the social optimum, ambient standards along a given river should allow increasing pollution concentrations

over distance as pollution evolves in the medium between upstream and downstream users.

Ambient standards are typically set at the national level, with enforcement of the standards delegated to states or cities. An example in the U.S. is California's Porter-Cologne Water Quality Control Act, which requires polluting entities such as municipal wastewater facilities to monitor water quality levels downstream from their operations in order to receive discharge permits for their pollution. In Germany some states have laws requiring that the concentration of ozone in cities must not exceed a certain concentration. In this case it is the problem of the local authorities to implement such ambient pollution levels. Several German cities, for example, enforce bans on the use of automobiles when urban air quality falls below some minimally acceptable threshold.^{||} Another policy option would be to implement taxes with varying tax rates according to the ambient pollution level.

Another area for future research is the optimal combination of emissions policies and ambient policies. SO₂ policy in the U.S. is determined jointly by cap and trade policy and by NAAQS on SO₂ as a criteria air pollutant. Yet these regulations appear to operate independently, with county attainment status under NAAQS regulations serving as an insignificant factor in county emissions levels (see Greenstone 2005). Clearly, there is scope to develop more efficient policies that jointly regulate emissions levels and ambient environmental quality levels, particularly in light of the superior performance of ambient standards that emerges throughout much of our analysis.

^{||}In fact, in this case, the short term policies are have not been proven to be very effective, and ambient pollution standards have often violated at hot summer days.

A Proofs

Proof of Proposition 1 (new): Rewriting the first order condition (3) as

$$-C_E \left(\frac{A}{\varphi} \right) = \varphi D_A(A, \delta) \quad (17)$$

differentiating with respect to A and applying the implicit function theorem, we obtain:

$$\frac{dA}{d\varphi} = - \frac{D_A(A, \delta) - \frac{A}{\varphi^2} C_{EE} \left(\frac{A}{\varphi} \right)}{\varphi D_{AA}(A, \delta) + \frac{1}{\varphi} C_{EE} \left(\frac{A}{\varphi} \right)} = - \frac{-C_E \left(\frac{A}{\varphi} \right) - E \cdot C_{EE} \left(\frac{A}{\varphi} \right)}{\varphi^2 D_{AA}(A, \delta) + C_{EE} \left(\frac{A}{\varphi} \right)}$$

where we used (17) in the last equation. Since the denominator is positive, we obtain the result.

$$E_{\varphi > \hat{\varphi}} \left\{ -C_E \left(\frac{A}{\varphi} \right) \frac{1}{\varphi} \right\} = D_A(A, \delta) [1 - F(\hat{\varphi}(A))]$$

Proof of equation (14): Differentiating (5) w.r.t. A yields:

$$E_{\varphi > \hat{\varphi}} \left\{ C_E \left(\frac{A}{\varphi}, I \right) \frac{1}{\varphi} \right\} + [E_{\varphi > \hat{\varphi}} \{ C_I \left(\frac{A}{\varphi}, I \right) \}] + \Gamma'(I) \frac{\partial I}{\partial A} \quad (18)$$

$$-C \left(\frac{A}{\hat{\varphi}(A, I)}, I \right) [\hat{\varphi}_A(A, I) + \hat{\varphi}_I(A, I) I'(A)] \quad (19)$$

$$+ D_A(A, \delta) \cdot [1 - F(\hat{\varphi}(A))] + E'_{\max}(I) I'(A) \int_{\varphi_l}^{\hat{\varphi}(A)} D_A(\varphi E_{\max}, \delta) \varphi dF(\varphi) \quad (20)$$

$$+ [D(\hat{\varphi}(A) E_{\max} - D(A)) f(\hat{\varphi}(A)) \hat{\varphi}'(A)] \quad (21)$$

Employing the firm's behavioral condition (12), the second term is zero. Further, since $A/\hat{\varphi}(A, I) = E_{\max}(I)$ by definition of $\hat{\varphi}(A)$, also the third term is zero. Finally again employing $\hat{\varphi}(A) E_{\max} = A$, also the final term is zero. Rearranging terms yields (FOC-A).

Proof of Proposition 2: Recall that $A^*(F)$ satisfies $D_A(A^*(F), \delta) = \int_{\varphi_l(F)}^{\varphi_h(F)} -C \left(\frac{A^*(F)}{\varphi} \right) \frac{1}{\varphi} dF(\varphi)$. By (7), we obtain:

$$0 = D_A(A^*(F), \delta) + \int_{\varphi_l(F)}^{\varphi_h(F)} C_E \left(\frac{A^*(F)}{\varphi} \right) \frac{1}{\varphi} dF(\varphi) > \int_{\varphi_l(G)}^{\varphi_h(G)} C_E \left(\frac{A^*(F)}{\varphi} \right) \frac{1}{\varphi} dG(\varphi) + D_A(A^*(F), \delta)$$

Thus $A^*(F)$ is not optimal with respect to G . Since under G the derivative of the expected marginal social cost is negative but increasing, social cost can be decreased by increasing A^* . Therefore $A^*(G) > A^*(F)$.

Proof of Proposition 3: Recall that $L^*(F)$ satisfies $-C_E(L^*(F)) = \int_{\varphi_l(F)}^{\varphi_h(F)} \varphi D_\varphi(\varphi L^*(F), \delta) dF(\varphi)$. By (9), we obtain:

$$0 = C_E(L^*(F)) + \int_{\varphi_l(F)}^{\varphi_h(F)} \varphi D_\varphi(\varphi L^*(F), \delta) dF(\varphi) < \int_{\varphi_l(G)}^{\varphi_h(G)} \varphi D_\varphi(\varphi L^*(F), \delta) dG(\varphi) + C_E(L^*(F))$$

Thus $L^*(F)$ is not optimal w.r.t. G . Since expected marginal damage under distribution G and standard $L^*(F)$ is larger than the marginal abatement cost, social cost can be decreased by decreasing L^* . Therefore $L^*(G) < L^*(F)$.

Proof of Proposition 4: For the proof we need the following Lemma:

Lemma 1 Define $\Gamma(\varphi, A) = C\left(\frac{A}{\varphi}\right)$. Then for A sufficiently large, $\Gamma_{\varphi\varphi} > 0$.

Proof of Lemma 1: We get $\Gamma_\varphi = C'\left(\frac{A}{\varphi}\right) \cdot \left(-\frac{A}{\varphi^2}\right)$ and $\Gamma_{\varphi\varphi} = A \left[\frac{A}{\varphi} C''\left(\frac{A}{\varphi}\right) + 2C'\left(\frac{A}{\varphi}\right) \right] / \varphi^3$. Now if A is sufficiently large, in particular if it is close to φE_{\max} , the term $C'\left(\frac{A}{\varphi}\right)$ gets arbitrarily close to zero. Since $C'' > 0$ by assumption, $\Gamma_{\varphi\varphi}$ will be positive.

Proof of Proposition 4 (continued): Ad i) First consider the case of a highly damaging pollutant with a large δ coefficient. Differentiating the equations (8) and (15) with respect to δ , it is straightforward to see that $\partial \bar{E}^* / \partial \delta < 0$, and $\partial A^* / \partial \delta < 0$. Thus a higher assessment of damage induces lower levels of emissions under both the emissions standard and the ambient standard. Since $\varphi_l > 0$, the ambient standard is always binding in all states of the world if δ is sufficiently high.

Now let $\bar{E}^* = \bar{E}^*(\delta)$ denote the optimal emissions standard for a given δ . Next let \tilde{A} be chosen such that the expected damage is the same under both the emission standard \bar{E}^* and the ambient standard $\tilde{A}(\bar{E}^*(\delta))$; that is,

$$D(\tilde{A}(\bar{E}^*(\delta)), \delta) = E_\varphi D(\varphi \bar{E}^*(\delta), \delta) \quad (22)$$

Now observe that by Jensen's inequality

$$E_\varphi D(\varphi \bar{E}, \delta) \geq D(\bar{\varphi} \bar{E}, \delta) \quad (23)$$

Let $D^{-1}(\cdot, \delta)$ be the inverse function to $D(\cdot, \delta)$. Since $D^{-1}(\cdot, \delta)$ is a positive monotonic function, applying this to (22) and using (23) yields

$$\tilde{A}(\bar{E}^*(\delta)) = D^{-1}(E_\varphi D(\varphi \bar{E}, \delta), \delta) \geq D^{-1}(D(\bar{\varphi} \bar{E}, \delta), \delta) = \bar{\varphi} \bar{E}. \quad (24)$$

Since $C(\cdot)$ is decreasing in E we obtain

$$C\left(\frac{\tilde{A}(\bar{E}(\delta))}{\bar{\varphi}}\right) \leq C\left(\frac{\bar{\varphi} \bar{E}(\delta)}{\bar{\varphi}}\right) = C(\bar{E}(\delta)) \quad (25)$$

Now choose δ sufficiently large such that the function $\Gamma(\varphi, \tilde{A}(\bar{E}^*(\delta))) = C\left(\frac{\tilde{A}(\bar{E}^*(\delta))}{\varphi}\right)$ is convex in φ . Next, consider the expected benefit of the standard \tilde{A} and apply Jensen's inequality to the function $\Gamma(\varphi, \tilde{A}) = C\left(\frac{\tilde{A}}{\varphi}\right)$, which is convex in φ for $\tilde{A} = \tilde{A}(\bar{E}^*(\delta))$. Doing so, and making use of (22) yields

$$E_\varphi C\left(\frac{\tilde{A}}{\varphi}\right) + D(\tilde{A}, \delta) = E_\varphi \Gamma(\varphi, \tilde{A}) + D(\tilde{A}, \delta) \quad (26)$$

$$< \Gamma(\bar{\varphi}, \tilde{A}) = C\left(\frac{\tilde{A}}{\bar{\varphi}}\right) + D(\tilde{A}, \delta) \quad (27)$$

$$\leq C(\bar{E}^*) + E_\varphi D(\varphi \bar{E}^*(\delta), \delta) \quad (28)$$

where the last inequality follows from (22) and (25) and the definition of \tilde{A} . Since \tilde{A} is not necessarily the optimal ambient standard with respect to δ , we obtain:

$$E_\varphi \{SC^A(A^*(\delta), \delta)\} \leq E_\varphi \{SC^A(\tilde{A}(\bar{E}^*(\delta)), \delta)\} < E_\varphi \{SC^{\bar{E}}(\bar{E}^*(\delta), \delta)\}$$

where $A^*(\delta)$ is the optimal ambient standard for δ .

Ad ii): A linear damage function is given by $D(A, \delta) = \delta A$. Now let $A^*(\delta)$ denote the optimal ambient standard for δ , and let $\tilde{E}(A^*(\delta))$ denote the emission standard that leads to the same expected damage as $A^*(\delta)$, i.e. $D(A^*(\delta)) = E_\varphi\{D(\varphi \cdot \tilde{E}(A^*(\delta)))\}$. Moreover let $\bar{E}^*(\delta)$ be the optimal emission standard for δ . By the linearity of the damage function we obtain $A^*(\delta) = E_\varphi\{\varphi \cdot \tilde{E}(A^*(\delta))\}$. If δ is sufficiently small but bounded away from zero, we have $\tilde{E}(A^*(\delta)) < E_{\max}$ but close to E_{\max} . Therefore also $A^*(\delta)/\bar{\varphi} = \tilde{E}(A^*(\delta)) < E_{\max}$ and $A^*(\delta)/\varphi < E_{\max}$ for $\varphi < \bar{\varphi}$ but sufficiently close to $\bar{\varphi}$. Now we know from Lemma 1 that $C(A/\varphi)$ is convex in φ if A/φ is sufficiently close to E_{\max} . Therefore Jensen's inequality yields

$$E_\varphi\{C(A/\varphi)\} > C(A/\bar{\varphi}) \quad (29)$$

This yields:

$$\begin{aligned} E_\varphi\{SC^A(A^*(\delta), \delta)\} &= E_\varphi\{C(A^*(\delta)/\varphi)\} + \delta A^* > C(A^*(\delta)/\bar{\varphi}) + \delta A^*(\delta) \\ &= C(\tilde{E}(A^*(\delta))) + \delta E_\varphi\{\varphi \tilde{E}(A^*(\delta))\} \\ &> C(E^*(\delta)) + \delta E_\varphi\{\varphi E^*(\delta)\} = E_\varphi\{SC^A(E^*(\delta), \delta)\} \end{aligned}$$

for some δ from some interval $[\underline{\delta}, \bar{\delta}]$ with $\underline{\delta} > 0$, and a suitable interval $[\varphi_l, \varphi_h]$.

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Figures:

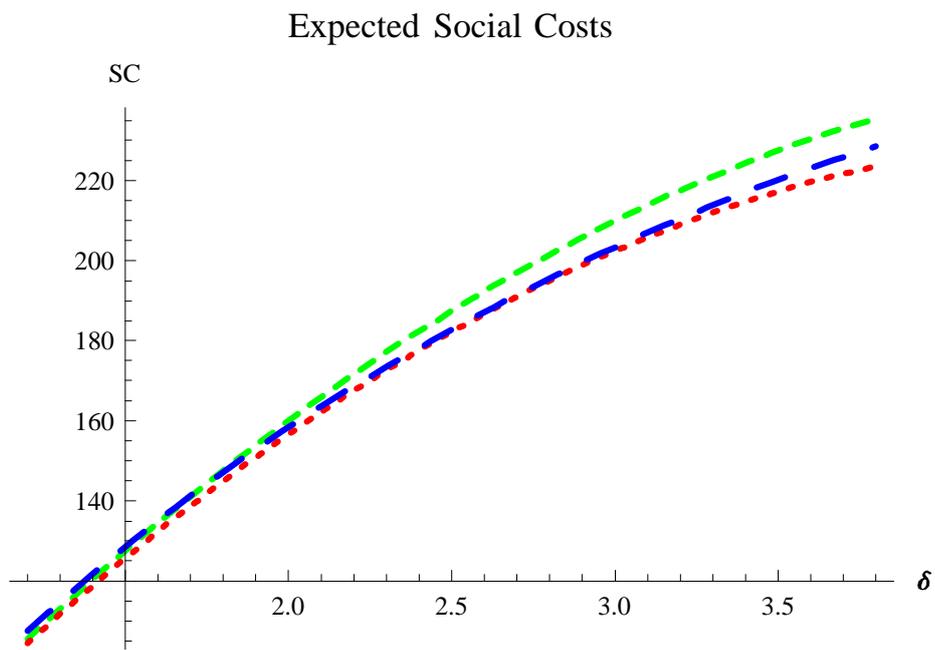


Figure 1: Model without pre-investment: Level of investment as a function of δ .
 Dotted Line: social optimum.
 Long dashes: ambient standard.
 Short dashes: emission cap.

Ambient Pollution Levels

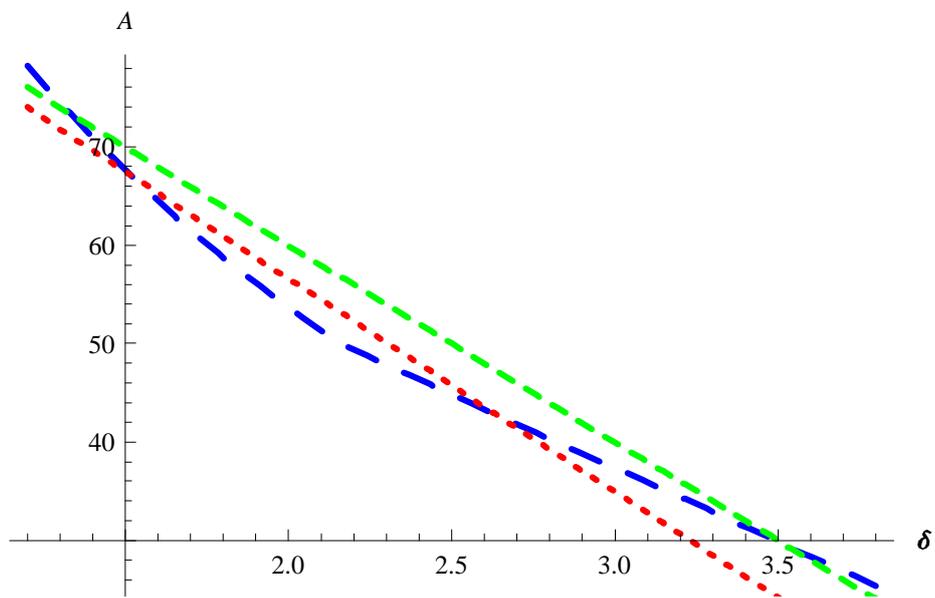


Figure 2: Model without pre-investment: ambient pollution as a function of δ .
Dotted Line: social optimum.
Long dashes: ambient standard.
Short dashes: emission cap.

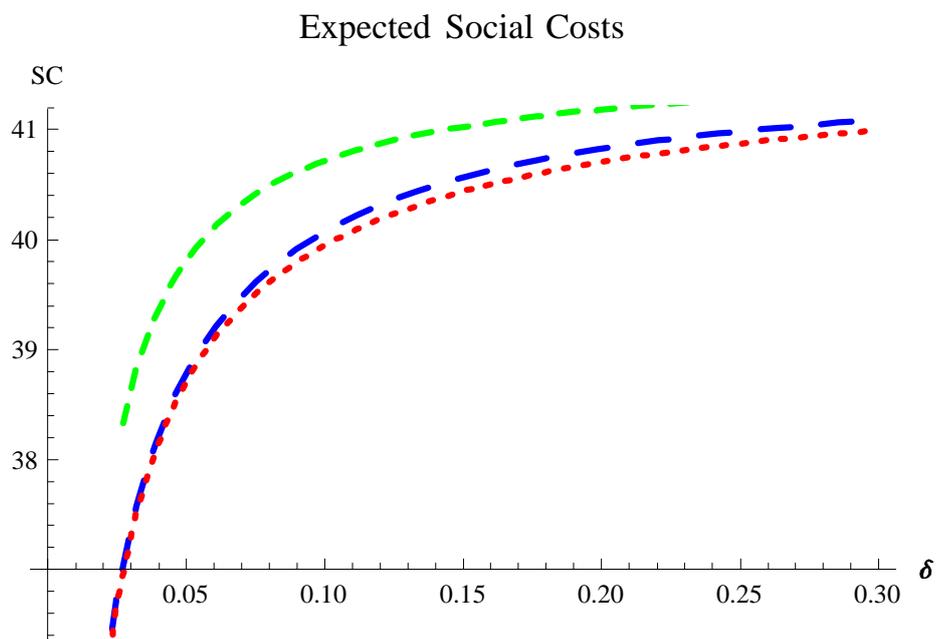


Figure 3: Model with pre-investment: Social as a function of δ .
 Dotted Line: social optimum.
 Long dashes: ambient standard.
 Short dashes: emission cap.

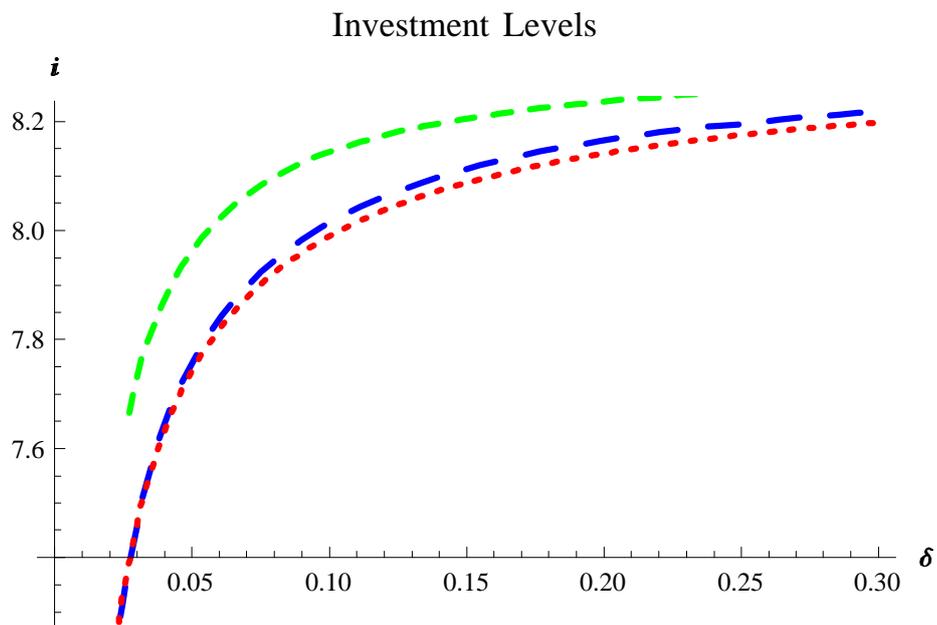


Figure 4: Model with pre-investment: Level of investment as a function of δ .
 Dotted Line: social optimum.
 Long dashes: ambient standard.
 Short dashes: emission cap.

Ambient Pollution

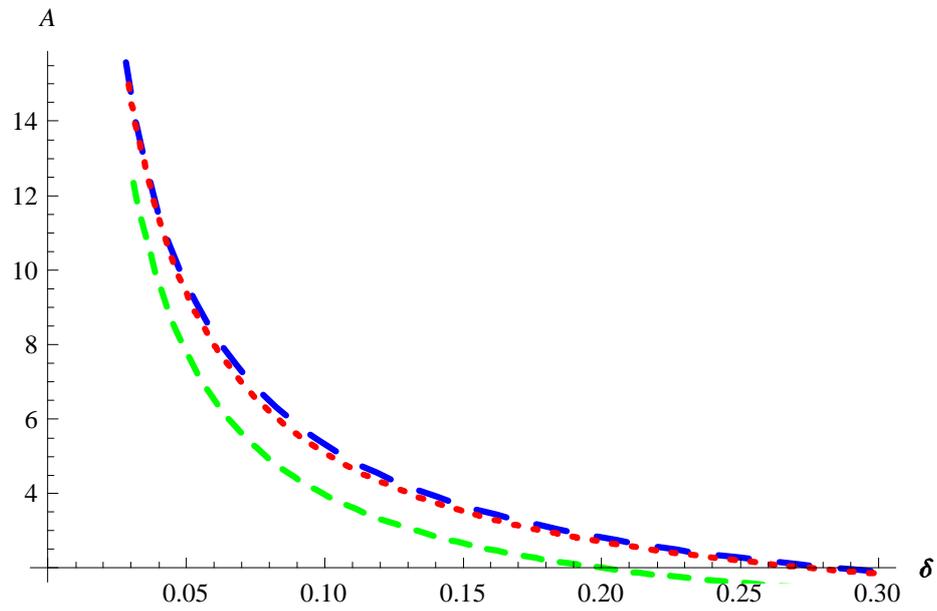


Figure 5: Model with pre-investment: (Expected ambient pollution as a function of δ).

Dotted Line: social optimum.

Long dashes: ambient standard.

Short dashes: emission cap.