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Insurance as a Private Emissions Wedge

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Abstract

This paper examines an environmental insurance contract where a firm's financial loss is endogenous, depending directly on its output and abatement decisions. In a three-stage game, a risk-averse monopolist chooses production, abatement, and insurance coverage, while the government precommits to an optimal emissions tax. Because financial losses increase with output, the insurance premium loading acts as a private emissions wedge. A higher loading factor raises the perceived marginal cost of dirty production, disciplining emissions by reducing output and encouraging abatement. Consequently, private risk pricing partially substitutes for public taxation, though this discipline stems from commercial insurance pricing rather than social marginal damage.

Keywords: Demand for insurance, Endogenous loss, Environmental loss, Environmental risk.

JEL Classification: C72, G22, H25, L12, Q54.

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1 Introduction

Environmental accidents and natural disasters have become increasingly relevant for firms' risk-management decisions. Human-induced climate change already affects several weather and climate extremes, including heavy precipitation, heat waves, droughts and tropical-cyclone-related rainfall (IPCC, 2023, Usman et al., 2025). At the same time, financial losses from natural catastrophes have reached historically high levels, regularly exceeding USD 100 billion per year in recent years (Swiss Re Institute, 2025).

This matters for firms because environmental damage is not only an ecological externality: it is also a balance-sheet risk. Corporate environmental insurance protects firms against remediation costs, legal costs, third-party compensation and other liabilities generated by environmental accidents (Zweifel and Tyran, 1994, Yin et al., 2011, Wen et al., 2024). Yet climate-related risks also make insurance more expensive and, in some cases, less available (Mills, 2005; Herweijer et al., 2009). Consistently with this trend, several jurisdictions have strengthened environmental-liability regimes and financial-security requirements. The European Environmental Liability Directive establishes an EU-wide polluter-pays liability regime; Spain requires mandatory financial security for certain operators under its environmental-liability legislation; and China has promoted compulsory environmental pollution liability insurance for selected high-risk enterprises (European Commission, 2024; Boletín Oficial del Estado, 2007; Ministry of Environmental Protection and China Insurance Regulatory Commission, 2013). Empirical evidence also suggests that environmental liability insurance is related to firms' environmental performance, pollution control and green innovation (Chen et al., 2022, Zhu et al., 2023, Shi et al., 2023, Wen et al., 2024). These facts raise a natural question: can market-loaded insurance premiums distort and discipline firms' real environmental behaviour, acting as a private emissions wedge without any deliberate regulatory design?

The mechanism studied in this paper is the *Private Emissions Wedge*. In standard insurance models, the premium is a monetary price for transferring an exogenous risk. Here, instead, the financial loss is endogenous because it depends on firms' emissions. When the insurance market is unfair, the endogenous insurance premium raises the perceived marginal cost of emissions. This is a private emissions wedge: it is not imposed by the government, and it is not chosen to equal marginal social damage. It emerges from the insurance-pricing mechanism. Nevertheless, because the financial loss is increasing in emissions, the insurance loading affects output, abatement and emissions.

This paper examines the behaviour of a monopoly firm, which chooses output and abatement, pays a unit tax on emissions, and purchases insurance against environmental accidents. The firm has logarithmic utility, meaning it is risk-averse and exhibits decreasing absolute risk aversion. There is a government that pre-commits to an optimal tax on emissions. In the fair-insurance benchmark, the loading factor is zero. We then compare this benchmark to a more realistic scenario involving unfair insurance in order to analyse the effects of the loading factor as a private emissions wedge.

The main result is that environmental insurance disciplines emissions. An increase in the loading factor lowers output, raises abatement and reduces emissions because it increases the expected marginal cost of the endogenous loss. This effect is unintended, determined by the natural pricing mechanism of the insurance market rather than a normative intervention.

The remainder of the paper is organised as follows. Section 2 summarises the relevant literature, and Section 3 presents the model. Section 4 derives the equilibrium, while Section 5 outlines the main result, namely, the role of insurance as a private emissions wedge. Section 6 examines how the equilibrium varies with changes in the parameters, and Section 7 concludes. All proofs are provided in the Appendix.

2 Related literature

The paper connects the theory of insurance demand to firms' real decisions and to environmental regulation. Classical analyses take the insured loss as given and characterise optimal coverage under expected utility (Smith, 1968; Mossin, 1968). A broader literature instead makes insurance part of a joint portfolio or production decision. Mayers and Smith (1983) show that portfolio composition and insurance demand are interdependent, while Eeckhoudt et al. (1997) formulate the joint demand for insurance and an insurable risky asset. This is the closest insurance-theory antecedent to the present mechanism: here output and abatement determine the emissions-dependent loss base, and the firm chooses coverage while anticipating the resulting insurance cost. Corporate insurance may also respond to underinvestment, limited liability, managerial incentives and firm characteristics (Schnabel and Roumi, 1989; MacMinn and Han, 1990; Han, 1996; Mayers and Smith, 1990). The strategic branch goes further by allowing insurance to alter firms' conduct in oligopoly (Ashby and Diacon, 1998; Seog, 2006). That mechanism is absent here: the firm is a monopolist and there is no rival whose behaviour can be influenced through coverage. The relevant interaction is instead between insurance pricing, the firm's output and abatement choices, and the government's emissions tax.

The distinction among market insurance, self-insurance and self-protection is essential. Market insurance transfers a share of the monetary loss; self-insurance reduces its magnitude; self-protection reduces its probability (Ehrlich and Becker, 1972). In the present model, the accident probability α is exogenous. Abatement therefore resembles self-insurance, not self-protection: it lowers emissions and hence the severity $x = \phi(q - z)$ of the firm's financial loss, while also reducing external environmental damage. It has a direct convex cost, $z^2/2$, but the model does not impose a resource constraint under which abatement expenditure is mechanically diverted from output. The theoretical relation between market insurance and private mitigation need not have a universal sign (Briys and Schlesinger, 1990; Courbage, 2001). Experiments likewise show that valuations depend on whether risk reduction changes loss probability or severity and on whether the risk is private or collective (Shogren, 1990); evidence on insurance and self-insurance often supports substitution (Pannequin et al., 2020). By contrast, Botzen et al. (2019) find, for households exposed to flood risk, that insurance complements measures adopted well before a disaster but substitutes for last-minute preparedness. Their setting is empirical and household-based, whereas the present model concerns a firm and a loss base that enters the premium schedule. Within the model, a larger loading factor reduces coverage and, at a given tax, induces more abatement because it makes each insured unit of emissions-dependent loss more expensive.

Actuarially fair insurance provides a disciplined benchmark for isolating this price channel. Under the standard expected-utility conditions in Mossin (1968), a fair proportional premium supports full coverage; a positive loading factor creates a wedge between the expected indemnity and its price and can generate partial coverage or non-purchase. The response of insurance demand to its price is nevertheless not automatic. Briys et al. (1989) derive sufficient conditions under which insurance is not a Giffen good, showing that strong wealth effects under DARA preferences can, in principle, overturn the ordinary substitution effect. However, such Giffen behaviour requires relative risk aversion to strictly exceed unity. In our logarithmic specification—a special case of CRRA utility with a relative risk aversion coefficient equal to one—insurance is unambiguously a normal good. This rules out Giffen outcomes while yielding a transparent DARA wealth effect and an explicit loading factor threshold above which coverage is zero. More importantly for the environmental result, the loading factor multiplies the endogenous loss base. It consequently affects the marginal returns to output and abatement rather than operating only as a price applied to a fixed risk. This distinguishes the present mechanism from models of incomplete markets, background risk or imprecisely observed losses (Doherty and Schlesinger, 1983; Eeckhoudt and Kimball, 1992; Gollier, 1996).

The environmental-liability literature provides the policy context. Zweifel and Tyran (1994) examine environmental impairment liability insurance as a policy instrument for environmental harm, while Yin et al. (2011) study whether insurance can address failures in the regulation of underground storage tanks. Related work analyses environmental risk under limited liability, moral hazard and public intervention (Boyer and Laffont, 1997; Hiriart et al., 2008). Natural-disaster insurance raises a related but distinct set of issues. Kunreuther (1996) proposes coupling insurance with enforced building codes to promote household mitigation. Muermann and Kunreuther (2008) show that, when self-protection creates positive interdependencies, deductibles or at-fault coverage can partially correct underinvestment. Both studies concern probability-reducing protection or disaster mitigation rather than emissions-dependent corporate loss severity. Ding and Deng (2024) provide closer evidence on firms: typhoon damage raises Chinese enterprises' property-insurance take-up through updated risk beliefs. Their analysis concerns learning and insurance purchase, however, not environmental liability, abatement or a premium base chosen by the insured firm.

Evidence on corporate environmental insurance, much of it from China, confirms that insurance and firms' environmental conduct are linked, but it does not imply a single behavioural mechanism. Environmental pollution liability insurance has been associated with better environmental performance or lower emissions in some studies (Zhu et al., 2023; Shi et al., 2023); other evidence indicates weaker pollution-treatment effort after insurance, consistent with moral hazard (Chen et al., 2022). Cassidy et al. (2026) find that a mandate improved environmental compliance on net because anticipated premium-based incentives outweighed, but did not eliminate, moral hazard among insured firms. Further studies examine green innovation, productivity and green transformation (Wen et al., 2024; Ma et al., 2025). These empirical designs do not identify the comparative statics of the loading factor in the present model, but they make the distinction between risk transfer and premium-based discipline economically relevant.

The closest theoretical environmental-insurance contributions are Colivicchi and Iannucci (2026) and Borghesi et al. (2026). In particular, in Borghesi et al. (2026), risk-averse firms in a duopoly choose between resilient and non-resilient production and demand insurance against disaster losses. The present paper studies a narrower structure in order to isolate a different margin: a monopolist chooses continuous output and abatement, its financial loss is proportional to emissions conditional on an accident, and the government pre-commits to an emissions tax. The contribution of the present paper is therefore deliberately narrow: it shows that an exogenous proportional insurance loading, when applied to an emissions-dependent loss base, enters the firm's marginal incentives regarding output, abatement and emissions and interacts with the optimal public tax. The model does not endogenise the accident probability, insurer behaviour or contract design, and it does not claim that insurance pricing generally implements social marginal environmental damage.

3 The model

Consider an economy with a monopolist that chooses output and abatement, and pays a unit tax on emissions. An environmental accident may occur and cause a financial loss, against which the firm may purchase insurance. The monopolist faces a linear inverse demand:

$$p = a - q. \tag{1}$$

3.1 The firm, emissions and environmental loss

The monopolist produces output q and chooses abatement z. Emissions are

$$e = q - z. \tag{2}$$

Thus, production raises emissions one for one, whereas abatement reduces them one for one. The monetary environmental loss is

$$x = e\phi = (q - z)\phi, \tag{3}$$

where $\phi > 0$ measures the severity of the financial loss generated by each unit of emissions.[1] The loss occurs with probability $\alpha \in [0, 1]$,[2] so that

$$\widetilde{x} = \begin{cases} x, & \text{with probability } \alpha, \\ 0, & \text{with probability } 1 - \alpha. \end{cases}$$

The expected environmental loss is $E\widetilde{x} = \alpha x$. Since x depends on output and abatement, the loss is endogenous.

[1] Alternatively, the financial loss could be modelled as depending on both the monopolist's emissions and an exogenous baseline level of emissions generated by other agents in the economy. However, adding such an exogenous component merely introduces a scale effect that does not alter the marginal incentives of either the firm or the government. It is therefore omitted for analytical simplicity.

[2] The probability of a climate-related environmental accident (α) is treated as exogenous because a single firm's emissions are negligible on a global scale and cannot alter the systemic frequency of such events. However, the firm's abatement efforts directly reduce its own local pollution footprint and the resulting financial liability if an accident occurs. Therefore, our model appropriately characterises abatement as self-insurance rather than self-protection.

Operating profits are

$$R = (p - c)q - \frac{z^2}{2} - (q - z)t,$$

where $c > 0$ is the marginal cost and $t > 0$ is the unit emissions tax. Let

$$\gamma \equiv a - c > 0,$$

denote market size. Using (1), operating profits become

$$R = (\gamma - q)q - \frac{z^2}{2} - (q - z)t. \tag{4}$$

The firm may insure the environmental loss. Let $\beta \in [0, 1]$ denote its coinsurance rate. If $\beta = 0$, the firm is uninsured; if $\beta = 1$, it is fully insured. Given the insurer's loading factor $\lambda \geqslant 0$, the premium is

$$P = (1 + \lambda)\alpha x \beta. \tag{5}$$

The actuarially fair component is $\alpha x \beta$, whereas $\lambda \alpha x \beta$ is the loading component. We compare the actuarially fair benchmark, $\lambda = 0$, with unfair insurance, $\lambda > 0$.

If the loss occurs, the firm's wealth is

$$W^L = R - (1 + \lambda)\alpha x \beta - (1 - \beta)x.$$

If the loss does not occur, its wealth is

$$W^N = R - (1 + \lambda)\alpha x \beta.$$

The firm is risk-averse and has logarithmic utility:

$$EU = \alpha \ln\left[R - (1 + \lambda)\alpha x \beta - (1 - \beta)x\right] + (1 - \alpha)\ln\left[R - (1 + \lambda)\alpha x \beta\right]. \tag{6}$$

Logarithmic utility exhibits decreasing absolute risk aversion: as wealth increases, the firm becomes less willing to pay for eliminating a given absolute risk. This property is appropriate for the present corporate-insurance problem (Eeckhoudt et al., 2005).

3.2 Government

The government pre-commits to a second-best unit tax on emissions in order to maximise social welfare:

$$SW = CS + CE + T - D. \tag{7}$$

In (7), $CS = \frac{q^2}{2}$ is consumer surplus, $CE = \exp(EU)$ is the certainty equivalent of the firm's expected utility, $T = te$ is tax revenue, and $D = \frac{e^2}{2}$ is environmental damage, which is distinct from the firm's financial loss x.

3.3 Timing

The game has three stages:

(i) the government chooses the unit emissions tax t to maximise social welfare;

(ii) the monopolist chooses output q and abatement z;

(iii) the monopolist chooses insurance coverage β.

The equilibrium concept is subgame-perfect equilibrium. The model is solved by backward induction.

4 Equilibrium

4.1 The coverage stage

In the third stage, R and x are given. Maximising (6) subject to $\beta \in [0, 1]$ gives the following result.

Proposition 1. *Suppose that* $x \in (0, R]$. *The monopolist's optimal insurance coverage is*

$$\beta^* = \begin{cases} 1, & \lambda = 0, \\ \dfrac{(1-\alpha)(1+\lambda)x - \lambda R}{[1-(1+\lambda)\alpha](1+\lambda)x}, & \lambda \in (0, \overline{\lambda}_\beta), \\ 0, & \lambda \geqslant \overline{\lambda}_\beta, \end{cases} \tag{8}$$

where

$$\overline{\lambda}_\beta \equiv \frac{(1-\alpha)x}{R-(1-\alpha)x}.$$

Under actuarially fair insurance, full coverage is optimal, as in Mossin (1968). A strictly positive loading makes full coverage suboptimal. For an intermediate loading, the firm purchases partial insurance; once the loading reaches $\overline{\lambda}_\beta$, the premium is sufficiently expensive that the firm remains uninsured. In the interval $(0, \overline{\lambda}_\beta)$, holding the loss fixed, higher operating profits reduce the coinsurance rate because logarithmic utility exhibits decreasing absolute risk aversion.

4.2 The market stage

In the second stage, the monopolist chooses output and abatement while anticipating its subsequent coverage decision. Substituting the interior solution $\beta^* \in (0,1)$ into (6) yields

$$EU = \ln\left[R - (1+\lambda)\alpha x\right] + \kappa(\alpha, \lambda), \tag{9}$$

where

$$\kappa(\alpha, \lambda) \equiv -\alpha \ln(1+\lambda) + (1-\alpha)\ln(1-\alpha) - (1-\alpha)\ln[1-(1+\lambda)\alpha].$$

Since the logarithm is strictly increasing and κ does not depend on q or z, maximising expected utility is equivalent to maximising

$$\begin{aligned} V(q,z) &= R - (1+\lambda)\alpha x \\ &= (\gamma - q)q - \frac{z^2}{2} - (q-z)t - (1+\lambda)(q-z)\alpha\phi, \end{aligned} \tag{10}$$

subject to $q \geqslant 0$, $z \geqslant 0$, and $q - z > 0$.[3] To ease the exposition, define

$$\overline{\lambda}_e \equiv \frac{\gamma - 3(t + \alpha\phi)}{3\alpha\phi}.$$

The next proposition summarises the outcome of the market stage.

Proposition 2. *Suppose $\lambda < \overline{\lambda}_e$. Then, the monopolist's interior market-stage choices are*

$$q^* = \frac{\gamma - t - (1+\lambda)\alpha\phi}{2}, \qquad z^* = t + (1+\lambda)\alpha\phi, \tag{11}$$

From Proposition 2, equilibrium emissions are

$$e^* = q^* - z^* = \frac{\gamma - 3[t + (1+\lambda)\alpha\phi]}{2}. \tag{12}$$

In what follows, we impose interior solutions in the coverage and market stages.

Assumption 1. *Let $\lambda \in [0, \overline{\lambda})$, where $\overline{\lambda} \equiv \min\{\overline{\lambda}_\beta, \overline{\lambda}_e\}$.*

We conclude the section by studying the effects of changes in the parameters in the market stage, by considering the emission tax as given.

Proposition 3. *At the market stage, an increase in the emissions tax, the loading factor, the severity of the financial loss, or the probability of an accident reduces output, increases abatement, and lowers emissions. A larger market increases output and emissions, while leaving abatement unchanged.*

Proposition 3 shows the different effects of changes in the tax, loading factor, severity of damage and probability of an environmental accident on equilibrium output and abatement. All these elements enter the firm's private marginal cost of emissions through the same additive term. Taken together, these effects reduce emissions. By contrast, market size raises the return to production but does not directly affect the marginal cost of abatement at this stage.

[3] We assume interior solutions with strictly positive emissions. Indeed, if $q - z = 0$, the financial loss vanishes, rendering environmental insurance redundant.

4.3 The government stage

The government problem is

$$\max_{t \geqslant 0} SW = CS + CE + T - D$$

where

$$\begin{aligned} CS &= \frac{[\gamma - t - (1+\lambda)\alpha\phi]^2}{8}, \\ CE &= \frac{\theta}{4}\left\{\gamma^2 - 2[t + (1+\lambda)\alpha\phi]\gamma + 3[t + (1+\lambda)\alpha\phi]^2\right\}, \\ T &= \frac{\{\gamma - 3[t + (1+\lambda)\alpha\phi]\}t}{2}, \\ D &= \frac{\{\gamma - 3[t + (1+\lambda)\alpha\phi]\}^2}{8}. \end{aligned}$$

and

$$\theta \equiv \exp[\kappa(\alpha, \lambda)] = \frac{(1-\alpha)^{1-\alpha}}{[1-(1+\lambda)\alpha]^{1-\alpha}(1+\lambda)^{\alpha}}.$$

Proposition 4. *Let Assumption 1 hold. The optimal emissions tax is*

$$t^* = \frac{(2-\theta)\gamma - (7-3\theta)(1+\lambda)\alpha\phi}{10-3\theta}. \tag{13}$$

By Proposition 4, the associated equilibrium choices are

$$\begin{aligned} q^*(t^*) &= \frac{(8-2\theta)\gamma - 3(1+\lambda)\alpha\phi}{2(10-3\theta)}, \\ z^*(t^*) &= \frac{(2-\theta)\gamma + 3(1+\lambda)\alpha\phi}{10-3\theta}, \\ e^*(t^*) &= \frac{4\gamma - 9(1+\lambda)\alpha\phi}{2(10-3\theta)}. \end{aligned} \tag{14}$$

In the benchmark case of an actuarially fair insurance premium, $\lambda = 0$, we obtain $\theta = 1$ and $\beta^* = 1$. For $\lambda \in (0, \overline{\lambda})$, coverage is interior and $\theta > 1$. The next corollary ensures that the optimal tax is positive.

Corollary 1. *The optimal emission tax is positive whenever*

$$\theta < \overline{\theta} \equiv \frac{2\gamma - 7(1+\lambda)\alpha\phi}{\gamma - 3(1+\lambda)\alpha\phi},$$

where $\overline{\theta} \in (0, 2)$ *for* $\gamma > \widehat{\gamma} \equiv \frac{7}{2}(1+\lambda)\alpha\phi$.

According to Corollary 1, in what follows we assume

Assumption 2. *Let* $\theta \in (0, \overline{\theta})$ *and* $\gamma > \widehat{\gamma}$.

5 Private emissions wedge

In this section, we show how insurance may act as a private emissions wedge. In the following Propositions, Assumption 1 and Assumption 2 hold. We develop our analysis in two directions.

First, by assuming an actuarially unfair premium, we analyse the effect of changes in the loading factor on output, abatement and emissions.

Proposition 5. *A higher loading factor decreases the optimal tax rate.*

A larger loading factor raises the premium paid for each unit of insured environmental loss. Since the loss base is increasing in aggregate emissions, the loading factor acts as a private marginal charge on emissions: it reduces output, encourages abatement and lowers the firm's equilibrium emissions before accounting for the government's tax response. The public emissions tax and the insurance loading factor are therefore partial substitutes. As the private emissions wedge becomes stronger, the government needs a lower Pigouvian-type tax to implement its objective. The government consequently reduces the public emissions tax. This substitution is not normatively designed by the insurer: the private wedge reflects insurance pricing rather than social marginal environmental damage.

Second, we study the comparison between an economy with actuarially fair insurance, $\lambda = 0$, and an economy with actuarially unfair insurance, $\lambda > 0$. This is the natural benchmark exercise when the object of interest is precisely the role of the loading factor. Indeed, the case $\lambda = 0$ removes the wedge between the actuarial value of coverage and its price: insurance is then a pure risk-sharing technology, so the resulting allocation measures the value of risk transfer in the absence of pricing distortions. Considering $\lambda > 0$ subsequently adds a well-defined market wedge, capturing the fact that real-world insurance premiums typically include administrative costs, monitoring and claims-verification costs, solvency and capital costs, and profit margins.

In the classical expected-utility framework, actuarially fair insurance is the canonical reference case, while a positive loading factor makes full insurance sub-optimal and can rationalise partial coverage (Mossin, 1968). Models of competitive insurance markets also formulate contracts in terms of insurance prices or odds and explain departures from fair pricing through informational frictions (Rothschild and Stiglitz, 1976). In the present model, by contrast, λ is an exogenous proportional loading rather than an equilibrium consequence of asymmetric information or insurer optimisation. Setting $\lambda = 0$ therefore removes precisely the private pricing wedge under study. It does not make the allocation first-best in every respect, because monopoly power and the environmental externality remain.

At $\lambda = 0$, $\theta = 1$ and (13) becomes

$$t^*(0) = \frac{\gamma - 4\alpha\phi}{7}.$$

By Proposition 5, t^* is strictly decreasing in λ. Hence

Proposition 6. *The optimal tax with a fair insurance premium is greater than the optimal tax with an unfair insurance premium.*

Proposition 6 clearly outlines the role of the loading factor in determining the emission wedge.

6 Effects of parameter changes

This section examines the equilibrium effects of market size, γ, and financial-loss severity, ϕ. The distinction between choice variables and derived outcomes is useful. The government's choice is t^*, while the monopolist chooses q^*, z^*, and β^*. Emissions $e^* = (q^* - z^*)$, the monetary environmental loss $x^* = \phi e^*$, operating profits R^*, the certainty equivalent CE^*, and social welfare SW^* are derived equilibrium outcomes.

Throughout this section, comparative statics are evaluated locally within the equilibrium intervals defined by Assumptions 1 and 2. When insurance is unfair, results based on the interior coverage formula strictly require $R^* > x^* > 0$ and $\beta^* \in (0, 1)$. Consequently, these comparative statics apply only as long as optimal demand for insurance is partial.

6.1 Market size

Begin with the effects of changes in market size for all equilibrium elements except equilibrium coverage. This will be dealt with separately.

Proposition 7. *An increase in market size raises the optimal emissions tax, output, abatement, emissions, the monetary environmental loss, operating profits, the firm's certainty equivalent, and social welfare.*

A larger market first raises the marginal return to production. At an unchanged policy, this would expand output and emissions without changing abatement. The government responds by increasing the emissions tax, which partially offsets the output expansion and induces additional abatement. The policy response is not strong enough to overturn the scale effect: equilibrium output and emissions both increase. Since $x^* = \phi e^*$ and ϕ is fixed, the monetary loss rises as well.

The same expansion raises operating profits and the certainty equivalent. These are conceptually different objects: R^* is operating profit before the stochastic environmental loss and insurance payments, whereas CE^* incorporates the risk and insurance consequences. Both nevertheless rise with market size in the maintained interior equilibrium. Social welfare also increases. These predictions are primarily theoretical. The empirical evidence is mechanism-consistent rather than a direct test. In particular, Shapiro and Walker (2018) show that US manufacturing output increased while pollution was being reduced through large changes in emissions intensity and environmental regulation, illustrating the distinction between a scale effect and a policy or technique effect. Moreover, Andersson (2019) provides causal evidence that a carbon tax can materially reduce emissions, supporting the policy-response channel that operates in the present model.

Proposition 8. *Under actuarially fair insurance, equilibrium coverage remains equal to one and is unaffected by market size. Conversely, under actuarially unfair insurance, there is a financial loss, denoted by $\widehat{x}$, such that partial demand for insurance increases as market size increases for $x < \widehat{x}$ and decreases for $x > \widehat{x}$.*

The results presented in equation Proposition 8 are relevant with regard to the behavioural properties of decreasing absolute risk aversion (DARA) utility functions. In the presence of endogenous loss, insurance coverage does not necessarily decrease with wealth; it can remain constant or even increase. This finding contrasts sharply with the existing literature on exogenous risk (Schlesinger, 2013). In classic exogenous models, DARA preferences dictate that as an agent's wealth increases, their absolute risk aversion decreases, directly leading to a reduction in demand for formal insurance. This standard wealth effect is economically driven by self-insurance: wealthier individuals have sufficient private financial reserves to absorb unmitigated shocks without significantly reducing their marginal utility.

However, when loss exposure is made endogenous, this baseline mechanism is fundamentally altered. Since the probability or magnitude of potential losses is linked to the agent's decisions, changes in wealth affect not only risk tolerance but also the marginal costs and benefits of self-protection or risk-taking activities. Consequently, the standard wealth effect is either significantly reduced or completely reversed, enabling insurance to behave as a normal good or even a luxury good, depending on the underlying risk technology.

Furthermore, the scale of the equilibrium financial loss x^* dictates how responsive insurance demand is to the size of the overall market. With large financial losses, the marginal cost of exposure grows rapidly in relation to market expansion. In this case, increases in market size lead to a shift away from insurance, causing coverage to behave as an inferior good. When x^* is relatively small, the financial burden of self-protection remains contained. In this case, the effect of market expansion dominates, enabling insurance demand to remain constant or even increase alongside market growth.

6.2 Financial-loss severity

An increase in the financial-loss severity parameter ϕ fundamentally alters the firm's cost structure by increasing the monetary liability generated by each unit of emissions. Unlike market size γ, which expands output scale, an increase in ϕ directly penalises dirty production conditional on an environmental accident.

Consistent with the analysis of market size, we first present the comparative-static effects that are monotonic in financial-loss severity, namely those on the emissions tax, production, emissions, and social welfare.

Proposition 9. *An increase in financial-loss severity decreases the emission tax, output, emissions and social welfare, while it raises abatement.*

The results in Proposition 9 are intuitive. Loss severity interacts directly with public regulatory policy. As private loss severity ϕ increases, the private risk environment naturally forces the firm to internalise potential environmental liabilities, prompting higher abatement and lower output. Because greater loss severity acts as an endogenous disciplining mechanism, the welfare-maximising regulator can lower the public emissions tax. This establishes a clear policy substitution: private risk pricing and financial liability substitute for public Pigouvian taxation.

We now turn to the effects on financial loss and demand for insurance. To characterise these comparative statics, we define:

$$\breve{\gamma} \equiv \frac{9}{2}(1+\lambda)\alpha\phi, \tag{15}$$

with $\breve{\gamma} > \widehat{\gamma}$.

Proposition 10. *An increase in financial-loss severity ϕ increases the expected financial loss and the optimal demand for insurance whenever market size is sufficiently large ($\gamma > \breve{\gamma}$).*

To understand the economic mechanism driving the comparative statics of expected monetary loss exposure (and, in turn, the demand for insurance), it is insightful to examine its analytical decomposition:

$$\frac{\partial x^*}{\partial \phi} = e^* + \phi\frac{\partial e^*}{\partial \phi}. \tag{16}$$

The first part of (16) is positive and shows that, for any remaining unmitigated unit of emissions, the monetary loss base becomes strictly more expensive due to the higher penalty per unit of environmental damage. The second part of (16) is negative, and shows that higher severity raises the expected marginal cost of dirty production. The firm responds by contracting output and expanding abatement expenditure, resulting in a direct reduction in physical emissions.

When market size is small ($\gamma < \breve{\gamma}$), the baseline scale of production is modest, allowing the negative, second effect to dominate and leading to an overall reduction in monetary loss exposure. Conversely, when market size is sufficiently large, the initial production scale and baseline emissions e^* are large enough that the first effect outweighs the negative one. In this regime, overall monetary loss exposure expands even though physical emissions e^* unambiguously decline.

The result of Proposition 10 can be explained by the increase in financial loss x^*, which, under large market sizes, directly shapes optimal insurance demand. As ϕ increases, the expanding monetary loss magnifies both the variance of the loss and its downside balance-sheet impact borne by the firm in the event of an accident. Under logarithmic utility (which exhibits DARA preferences), this heightened downside exposure increases the firm's marginal valuation of risk transfer. Consequently, the firm increases its coverage rate, accepting the higher loading burden of unfair insurance to protect its balance sheet.

Finally, we study the effects on profits. Define:

$$\overline{\gamma} \equiv \frac{9(17-6\theta)}{4(7-3\theta)}(1+\lambda)\alpha\phi.$$

Proposition 11. *An increase in financial-loss severity ϕ increases operating profits whenever market size is sufficiently large ($\gamma > \overline{\gamma}$) and decreases them for $\gamma < \overline{\gamma}$.*

The economic intuition of Proposition 11 is particularly transparent if the derivative of operating profits is written using the market-stage first-order conditions. Since

$$R = (\gamma - q)q - \frac{z^2}{2} - t(q - z),$$

and

$$\gamma - 2q^* - t^* = (1+\lambda)\alpha\phi, \qquad t^* - z^* = -(1+\lambda)\alpha\phi,$$

we obtain

$$\frac{\partial R^*}{\partial \phi} = (1+\lambda)\alpha\phi\frac{\partial e^*}{\partial \phi} - e^*\frac{\partial t^*}{\partial \phi}.$$

The first part is negative: greater loss severity strengthens the firm's private marginal cost of emissions, inducing lower output and higher abatement, and the resulting contraction in emissions is costly in terms of operating profits. The second part is positive because the government responds to the stronger private emissions wedge by reducing the emissions tax. Hence, higher severity produces two opposing effects on operating profits: a negative real-adjustment effect and a positive tax-relief effect. For relatively small and intermediate markets, the former dominates and operating profits fall. For sufficiently large markets, however, the tax reduction applies to a large remaining emissions base, so that the associated saving in tax payments eventually dominates the adjustment cost. Operating profits therefore rise rather than fall when γ is sufficiently large.

These predictions are broadly consistent with empirical evidence. Changes in environmental-liability rules provide the closest empirical analogue to an increase in the effective financial cost of residual pollution. Alberini and Austin (2002) find that strict liability under US state mini-Superfund laws reduces the frequency and severity of unintended pollution releases. Akey and Appel (2021) show that stronger parent-company limited-liability protection increases toxic emissions, with the effect operating mainly through lower investment in pollution-abatement technologies rather than greater production. Similarly, Chen et al. (2025) find that the *Apex Oil* ruling, which increased the effective exposure of financially vulnerable firms to environmental clean-up liabilities, induced more pollution-prevention activity and lower emissions while simultaneously worsening their financing conditions. Taken together, these findings support the mechanism whereby greater exposure to environmental losses strengthens incentives to reduce pollution, although they do not constitute a direct test of the model's parameter ϕ or of its operating-profit comparative static.

Evidence from environmental insurance itself is more heterogeneous. Zhu et al. (2023) find that China's Environmental Pollution Liability Insurance programme reduced emissions and identify prospective premium savings as an important incentive for firms to improve environmental performance. Cassidy et al. (2026) likewise document substantial improvements in environmental compliance following a pollution-liability-insurance mandate and find evidence consistent with anticipatory premium-based incentives. However, Shi et al. (2023), while also finding lower pollution, attribute an important role to public supervision and corporate self-discipline and report only a limited marginal role for insurance premia. Chen et al. (2022) instead find evidence of moral hazard, with environmental insurance reducing firms' pollution-treatment effort. The empirical evidence therefore supports the general idea that environmental insurance affects firms' environmental choices, but it also shows that the direction and mechanism depend on contract design and institutional conditions.

The institutional design of China's environmental-liability-insurance system provides a particularly relevant real-world counterpart to the model's pricing mechanism. Official guidelines require insurers to incorporate environmental risk, previous pollution accidents, regulatory compliance, production technology, firm scale and local environmental sensitivity into premium determination (Ministry of Environmental Protection of the People's Republic of China and China Insurance Regulatory Commission, 2013). This is not the simple proportional loading assumed in the model, but it illustrates the same economic principle: when environmental behaviour affects the price of risk transfer, insurance pricing can enter firms' marginal incentives to pollute or abate. By contrast, the comparative-static prediction that the public emissions tax falls as private loss severity rises has no direct counterpart in the studies cited above, which do not estimate whether environmental regulators systematically adjust tax rates in response to changes in firms' private liability exposure. Likewise, these studies do not identify the model's market-size threshold separating the valuation and quantity effects on monetary loss exposure. These remain empirically testable implications of the framework.

7 Conclusions

This paper studies an environmental insurance contract in which the financial loss due to an environmental accident was endogenous to firms' product-market and abatement decisions. A risk-averse monopolist chooses output and abatement, pays an emissions tax, and buys insurance against an environmental accident whose monetary loss depended on aggregate emissions. The government sets the optimal emission tax. The central result is that the insurance loading operated as a private emissions wedge. The loading is not set as a wedge to implement a Pigouvian rule or to internalise social marginal damages. Nevertheless, because financial losses increased with emissions, the loading raises the firm's perceived marginal cost of dirty production. As a result, insurance reduces output, increases abatement, lowers emissions and physical losses, and generates partial rather than full insurance coverage. Environmental insurance therefore disciplines emissions, but it did so through private incentives rather than through an explicit environmental-policy objective.

The analysis also had some limitations. First, the model deliberately used a monopolistic industry. This made the private-emissions-wedge mechanism transparent, but it excluded firms' strategic interaction, asymmetric technologies, or differentiated products. Secondly, the environmental loss was assumed to be linear in aggregate emissions and the accident probability was treated as exogenous. This ruled out nonlinear damage functions, threshold effects, fat-tailed environmental risks, and feedback from prevention or abatement to the probability of an accident. Finally, the insurance contract was represented by a single coinsurance rate and a proportional premium loading. This excluded deductibles, caps, experience-rating histories, contract menus, adverse selection, moral hazard in accident prevention, and regulatory constraints on insurance pricing.

The analysis can be extended in several directions. A first development would be to introduce an oligopolistic industry. In particular, allowing for asymmetric firms would make it possible to consider differences in productivity, environmental efficiency, risk aversion, balance-sheet strength, or baseline exposure to environmental losses. This would make it possible to study whether insurance market power reallocates production towards cleaner or dirtier firms. A second extension would be to enrich the insurance contract by allowing deductibles, coverage limits, nonlinear premia, or menus of contracts designed by the insurer. This would also clarify whether the private emissions wedge is strengthened or weakened once the insurer can use more instruments than a proportional loading. Finally, a dynamic version of the model could allow emissions to accumulate, abatement to have persistent effects, and insurance premia to depend on firms' past environmental performance. Such an extension would be particularly useful for studying whether environmental insurance can create durable incentives for green investment rather than only short-run reductions in output and emissions. These developments are left for future research.

Appendix

Proof of Proposition 1

The first-order condition of (6) with respect to β is:

$$\frac{\partial EU}{\partial \beta} = \left[\frac{x-(1+\lambda)\alpha x}{R-(1+\lambda)\alpha x\beta-(1-\beta)x}\right]\alpha + \left[\frac{-(1+\lambda)\alpha x}{R-(1+\lambda)\alpha x\beta}\right](1-\alpha) = 0. \quad (17)$$

Solving (17), one obtains:

$$\beta_i = \frac{(1+\lambda)(1-\alpha)x-\lambda R}{[1-(1+\lambda)\alpha](1+\lambda)x}.$$

Since $R - x \geqslant 0$ (Eeckhoudt et al., 2005), we have:

$$\beta = \begin{cases} 1 & \forall\lambda \in \{0\} \cup \left(\frac{(1-\alpha)x}{\alpha x}, \frac{R-\alpha x}{\alpha x}\right], \\ \frac{(1+\lambda)(1-\alpha)x-\lambda R}{[1-(1+\lambda)\alpha](1+\lambda)x} & \forall\lambda \in \left(0, \frac{(1-\alpha)x}{R-(1-\alpha)x}\right) \cup \left(\frac{R-\alpha x}{\alpha x}, +\infty\right). \\ 0 & \forall\lambda \in \left[\frac{(1-\alpha)x}{R-(1-\alpha)x}, \frac{(1-\alpha)x}{\alpha x}\right). \end{cases}$$

Notice that $\beta = 1$ for $\lambda \in \left\{0, \frac{R-\alpha x}{\alpha x}\right\}$. However, for $\lambda = \frac{R-\alpha x}{\alpha x}$ the insurance premium is higher than for $\lambda = 0$, and so it is not rational for the firm to take out an insurance contract with the same coverage but at a higher price. The same reasoning applies for $\lambda \in \left(\frac{R-\alpha x}{\alpha x}, +\infty\right)$ and for $\lambda \in \left(\frac{(1-\alpha)x}{R-(1-\alpha)x}, \frac{(1-\alpha)x}{\alpha x}\right)$. Denoting

$$\overline{\lambda}_\beta \equiv \frac{(1-\alpha)x}{R-(1-\alpha)x},$$

we have $\beta^* \in (0,1)$ for $\lambda \in (0, \overline{\lambda}_\beta)$. Finally, this implies that the denominator of β^* for $\lambda < \overline{\lambda}$ is positive, and thus $1-(1+\lambda)\alpha > 0$ for every $x \in (0, R]$. □

Proof of Proposition 2

The first-order conditions for (10) are

$$\frac{\partial V}{\partial q} = \gamma - 2q - t - (1+\lambda)\alpha\phi = 0, \qquad \frac{\partial V}{\partial z} = -z + t + (1+\lambda)\alpha\phi = 0. \quad (18)$$

Since $\frac{\partial^2 V}{\partial q^2} = -2$, $\frac{\partial^2 V}{\partial z^2} = -1$, $\frac{\partial^2 V}{\partial q \partial z} = 0$, the stationary point (q^*, z^*) is a global maximum. Solving the first-order conditions yields (11). Since $z^* > 0$, $q^* - z^* > 0$ ensures positive emissions, i.e., $\lambda < \overline{\lambda}_e$. □

Proof of Proposition 3

Direct differentiation of (11) and (12) gives

$$\frac{\partial q^*}{\partial t} = -\frac{1}{2}, \qquad \frac{\partial z^*}{\partial t} = 1, \qquad \frac{\partial e^*}{\partial t} = -\frac{3}{2},$$

$$\frac{\partial q^*}{\partial \alpha} = -\frac{(1+\lambda)\phi}{2} < 0, \ \frac{\partial q^*}{\partial \phi} = -\frac{(1+\lambda)\alpha}{2} < 0, \ \frac{\partial q^*}{\partial \lambda} = -\frac{\alpha\phi}{2} < 0,$$

$$\frac{\partial z^*}{\partial \alpha} = (1+\lambda)\phi > 0, \ \frac{\partial z^*}{\partial \phi} = (1+\lambda)\alpha > 0, \ \frac{\partial z^*}{\partial \lambda} = \alpha\phi > 0,$$

$$\frac{\partial e^*}{\partial \alpha} = -\frac{3(1+\lambda)\phi}{2} < 0, \ \frac{\partial e^*}{\partial \phi} = -\frac{3(1+\lambda)\alpha}{2} < 0, \ \frac{\partial e^*}{\partial \lambda} = -\frac{3\alpha\phi}{2} < 0,$$

and

$$\frac{\partial q^*}{\partial \gamma} = \frac{1}{2}, \qquad \frac{\partial z^*}{\partial \gamma} = 0, \qquad \frac{\partial e^*}{\partial \gamma} = \frac{1}{2}.$$

□

Proof of Proposition 4 and Corollary 1

Substituting the market-stage equilibrium into (7) yields

$$SW = \frac{1}{4}\{\theta\gamma^2 - 2[t + (1+\lambda)\alpha\phi]\theta\gamma + 2[t + (1+\lambda)\alpha\phi]\gamma + 2t\gamma + (3\theta - 4)[t + (1+\lambda)\alpha\phi]^2 + \\ - 6[t + (1+\lambda)\alpha\phi]t\}.$$

The first-order condition is

$$\frac{\partial SW}{\partial t} = \frac{1}{2}[(2-\theta)\gamma + (3\theta - 7)(1+\lambda)\alpha\phi + (3\theta - 10)t] = 0.$$

Solving gives (13). The second-order condition is

$$\frac{\partial^2 SW}{\partial t^2} = -\frac{10 - 3\theta}{2} < 0,$$

which holds for $\theta < 10/3$. Notice that $t^* > 0$ for

$$\theta < \overline{\theta} \equiv \frac{2\gamma - 7(1+\lambda)\alpha\phi}{\gamma - 3(1+\lambda)\alpha\phi},$$

which is positive for

$$\gamma > \widehat{\gamma} \equiv \frac{7}{2}(1+\lambda)\alpha\phi.$$

Therefore conditions $\theta < \overline{\theta}$ and $\gamma > \widehat{\gamma}$ ensure positive emission tax. Moreover, notice that $\overline{\theta} < 10/3$, so t^* is always a global maximum point. Substituting t^* into the market-stage choices gives (14).

We now show that $\bar{\theta} < 2$. First, notice that the denominator of $\bar{\theta}$ is

$$\gamma - 3(1+\lambda)\alpha\phi,$$

is positive. This is because

$$\gamma > \frac{7}{2}(1+\lambda)\alpha\phi(= \widehat{\gamma}).$$

We can therefore compare $\bar{\theta}$ with 2 directly:

$$\bar{\theta} < 2 \iff \frac{2\gamma - 7(1+\lambda)\alpha\phi}{\gamma - 3(1+\lambda)\alpha\phi} < 2,$$

which can be rewritten as

$$2\gamma - 7(1+\lambda)\alpha\phi < 2\gamma - 6(1+\lambda)\alpha\phi \iff -(1+\lambda)\alpha\phi < 0,$$

which is always true. Hence $\bar{\theta} < 2$.

$\square$

Proof of Proposition 5

Differentiating (13) with respect to the loading factor and collecting terms gives

$$\frac{\partial t^*}{\partial \lambda} = -\frac{(7-3\theta)(10-3\theta)\alpha\phi + [4\gamma - 9(1+\lambda)\alpha\phi]\frac{\partial\theta}{\partial\lambda}}{(10-3\theta)^2}, \tag{19}$$

where
$$\frac{\partial \theta}{\partial \lambda} = \frac{\alpha\lambda\theta}{[1-(1+\lambda)\alpha]\,(1+\lambda)} > 0.$$

Under Assumption 2, $\theta \in [1, \overline{\theta})$ and $\gamma > \widehat{\gamma}$, so every term in the numerator of (19) is non-negative. This yields the proposition. □

Proof of Proposition 7

It is easy to check that

$$\begin{aligned}
\frac{\partial t^*}{\partial \gamma} &= \frac{2}{10-3\theta} > 0, \\
\frac{\partial q^*}{\partial \gamma} &= \frac{4}{10-3\theta} > 0, \\
\frac{\partial z^*}{\partial \gamma} &= \frac{2}{10-3\theta} > 0, \\
\frac{\partial e^*}{\partial \gamma} &= \frac{2}{10-3\theta} > 0, \\
\frac{\partial x^*}{\partial \gamma} &= \frac{2\phi}{10-3\theta} > 0.
\end{aligned}$$

From the first-order conditions (18), we can write the optimal operating profits as

$$R^* = (q^*)^2 + \frac{(z^*)^2}{2} + (q^* - z^*)(1+\lambda)\alpha\phi.$$

Differentiating with respect to market size yields

$$\frac{\partial R^*}{\partial \gamma} = 2q^* \frac{\partial q^*}{\partial \gamma} + z^* \frac{\partial z^*}{\partial \gamma} + \left(\frac{\partial q^*}{\partial \gamma} - \frac{\partial z^*}{\partial \gamma} \right) (1+\lambda)\alpha\phi > 0.$$

Since
$$CE^* = \left[(q^*)^2 + \frac{(z^*)^2}{2} \right] \theta,$$

we have
$$\frac{\partial CE^*}{\partial \gamma} = \left[2q^* \frac{\partial q^*}{\partial \gamma} + z^* \frac{\partial z^*}{\partial \gamma} \right] \theta > 0.$$

Recall that
$$SW^* = CS^* + CE^* + T^* - D^*,$$

where

$$
\begin{aligned}
CS^* &= \frac{(q^*)^2}{2}, \\
T^* &= (q^* - z^*)t^*, \\
D^* &= \frac{(q^* - z^*)^2}{2}.
\end{aligned}
$$

So,

$$
\begin{aligned}
\frac{\partial SW^*}{\partial \gamma} = & \left(2q^* \frac{\partial q^*}{\partial \gamma} + z^* \frac{\partial z^*}{\partial \gamma}\right) \theta + \left(\frac{\partial q^*}{\partial \gamma} - \frac{\partial z^*}{\partial \gamma}\right) t^* + (q^* - z^*) \frac{\partial t^*}{\partial \gamma} + \\
& \left(q^* \frac{\partial z^*}{\partial \gamma} - \frac{\partial z^*}{\partial \gamma}\right) z^* > 0.
\end{aligned}
$$

□

Proof of Proposition 8

Differentiating the optimal partial insurance coverage we obtain

$$
\begin{aligned}
\frac{\partial \beta^*}{\partial \gamma} &= \frac{\left[(1-\alpha)(1+\lambda)\frac{\partial x^*}{\partial \gamma} - \lambda \frac{\partial R^*}{\partial \gamma}\right][1-(1+\lambda)\alpha](1+\lambda)x^*}{[1-(1+\lambda)\alpha]^2(1+\lambda)^2(x^*)^2} + \\
&- \frac{[(1-\alpha)(1+\lambda)x^* - \lambda R^*][1-(1+\lambda)\alpha](1+\lambda)\frac{\partial x^*}{\partial \gamma}}{[1-(1+\lambda)\alpha]^2(1+\lambda)^2(x^*)^2} \\
&= \frac{\left[(1-\alpha)(1+\lambda)\frac{\partial x^*}{\partial \gamma} - \lambda \frac{\partial R^*}{\partial \gamma}\right]x^* - [(1-\alpha)(1+\lambda)x^* - \lambda R^*]\frac{\partial x^*}{\partial \gamma}}{[1-(1+\lambda)\alpha](1+\lambda)(x^*)^2} \\
&= \frac{\left(R^* \frac{\partial x^*}{\partial \gamma} - x^* \frac{\partial R^*}{\partial \gamma}\right)\lambda}{[1-(1+\lambda)\alpha](1+\lambda)(x^*)^2}.
\end{aligned}
$$

It is immediate to see that $\frac{\partial \beta^*}{\partial \gamma} = 0$ under actuarially fair insurance ($\lambda = 0$). When $\lambda > 0$, we know that $\frac{R^*}{x^*} \geqslant 0$ and $\frac{\partial R^*}{\partial \gamma} > \frac{\partial x^*}{\partial \gamma}$. This implies that if $x^* = R^*$, then $R^* \frac{\partial x^*}{\partial \gamma} - x^* \frac{\partial R^*}{\partial \gamma} < 0$, and so $\frac{\partial \beta^*}{\partial \gamma} < 0$, the opposite is true for $x^* \to 0$. Therefore, we can conclude that for small financial loss $\frac{\partial \beta^*}{\partial \gamma} \geqslant 0$, while for high financial loss $\frac{\partial \beta^*}{\partial \gamma} < 0$. □

Proof of Proposition 9

It is easy to check:

$$\begin{aligned}
\frac{\partial t^*}{\partial \phi} &= -\frac{(7-3\theta)(1+\lambda)\alpha}{10-3\theta}, \\
\frac{\partial q^*}{\partial \phi} &= -\frac{3(1+\lambda)\alpha}{2(10-3\theta)}, \\
\frac{\partial z^*}{\partial \phi} &= \frac{3(1+\lambda)\alpha}{10-3\theta}, \\
\frac{\partial e^*}{\partial \phi} &= -\frac{9(1+\lambda)\alpha}{2(10-3\theta)}.
\end{aligned}$$

Notice that $7-3\theta>0$ for $\gamma>\hat{\gamma}$.

□

Proof of Proposition 10

Differentiating the social welfare with respect to ϕ, we get

$$\frac{\partial SW^*}{\partial \phi} = -\frac{4\gamma-9(1+\lambda)\alpha\phi}{2(10-3\theta)} = -e^*,$$

and thus always negative. Differentiating the monetary environmental loss with respect to ϕ, we get

$$\frac{\partial x^*}{\partial \phi} = \frac{2\gamma-9(1+\lambda)\alpha\phi}{10-3\theta}. \tag{20}$$

So, $\frac{\partial x^*}{\partial \phi}>0$ for

$$\gamma > \breve{\gamma} \equiv \frac{9}{2}(1+\lambda)\alpha\phi.$$

The opposite, $\frac{\partial x^*}{\partial \phi}<0$, is true for $\gamma<\breve{\gamma}$. To elicit some economic intuition, it is useful to rewrite (20) using the formulas for e^* and $\frac{\partial e^*}{\partial \phi}$, that is

$$\frac{\partial x^*}{\partial \phi} = e^* + \phi\frac{\partial e^*}{\partial \phi}.$$

Differentiating the optimal coverage with respect to ϕ, we get

$$\frac{\partial \beta^*}{\partial \phi} = \frac{\left(R^* \frac{\partial x^*}{\partial \phi} - x^* \frac{\partial R^*}{\partial \phi}\right)\lambda}{[1-(1+\lambda)\alpha](1+\lambda)(x^*)^2}.$$

We can rewrite

$$R^* \frac{\partial x^*}{\partial \phi} - x^* \frac{\partial R^*}{\partial \phi} = \frac{81(1+\lambda)^2\alpha^2\phi^2\gamma + [(10-3\theta)^2+8][2\gamma - 9(1+\lambda)\alpha\phi]\gamma^2}{6(10-3\theta)^2},$$

positive for $\gamma > \breve{\gamma}$. □

Proof of Proposition 11

Differentiating the operating profits with respect to ϕ, we get

$$\frac{\partial R^*}{\partial \phi} = \frac{[4(7-3\theta)\gamma - 9(17-6\theta)(1+\lambda)\alpha\phi](1+\lambda)\alpha}{2(10-3\theta)^2}.$$

We know that $\theta \geqslant 1$, with equality for $\lambda = 0$ and $\theta > 1$ for $\lambda > 0$. Moreover, $\bar{\theta} < 2$ by Corollary 1. Hence $7 - 3\theta > 0$ and the relevant profit threshold is

$$\overline{\gamma} \equiv \frac{9(17-6\theta)}{4(7-3\theta)}(1+\lambda)\alpha\phi.$$

Moreover, $\overline{\gamma} > \breve{\gamma}$, because, for $\theta \in [1, 2)$,

$$\frac{9(17-6\theta)}{4(7-3\theta)} \in \left[\frac{99}{16}, \frac{45}{4}\right).$$

Hence, for a sufficiently large market, if $\gamma > \overline{\gamma}$, then $\frac{\partial R^*}{\partial \phi} > 0$.

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