Competition and Preventive Investments in Climate Insurance

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Abstract

Insurance markets face increasing and non-diversifiable climate risks. Investments in climate adaptation measures can mitigate these risks. However, insurers underinvest in these public goods when they cannot internalise all the benefits of risk-reduction due to competition in the industry. I develop a model of investments in preventive measures by natural catastrophe insurance companies. By modeling how insurers' pricing and investment strategies vary with market structure, I examine the policy trade-off between competition and investment. Monopoly insurance markets result in a higher level of preventive investment than the combined Bertrand duopoly market; this result reverses the Arrow (1962) replacement theory of competition and process innovation when extended to non-appropriable innovation. Moreover, the monopoly markup over competitive prices is bounded above by price elasticity of demand and could even be negative. Thus, insurers can expand insurance coverage by mitigating risk from investments in public preventive measures, in absence of competition concerns.

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'As soon as we go into details and inquire into the individual items in which progress was most conspicuous, the trail leads not to the doors of those firms that work under conditions of comparatively free competition but precisely to the doors of the large concerns . . . and a shocking suspicion dawns upon us that big business may have had more to do with creating that standard of life than with keeping it down.'

—Schumpeter (1942, 82)

1 Introduction

Natural catastrophe insurance differs from traditional insurance models by insuring against non-diversifiable risks. Traditional insurance operates by diversifying this risk across a large pool of policyholders, but catastrophe risks are highly correlated across individual policyholders in the same region. Insurance companies use financial measures such as reinsurance and debt instruments to reduce exposure to these non-diversifiable risks. However, insurers face a natural limit to spreading these risks when there exists increasing and non-diversifiable catastrophe risk due to climate change. Insurance in high climate risk areas have started unraveling as a result. This paper provides a model of investments in preventive measures by climate insurance companies to reduce these insured risks.

In this paper, I study how industry competition affects preventive investments by firms. Preventive investments for natural catastrophe (natcat) risks are primarily adaptation and mitigation infrastructure, which are public goods in nature. Thus, the usual factors which constrain supply of public goods in equilibrium apply to preventive investments: coordination failures and competition concerns. Competition in the industry could reduce insurers' investments in public preventive goods as they cannot internalize all the benefits of their investments. Thus, insurers would have a lower incentive to supply public preventive measures in competitive markets. On the other hand, Arrow's traditional result on competition and investments in cost-reduction technology suggests that such investments are increasing with competition and a monopolist firm has the least incentive to innovate. This paper models competition and prevention investment in natcat insurance industry to examine this question. This also allows us to examine the policy tradeoff between competition and preventive investments: does increasing competition in insurance industry lowers preventive investments by natcat insurance companies?

This paper makes two contributions to the literature: first, it is the first paper to provide a model of investments by insurance companies in prevention of natural catastrophes. By modeling how insurers' pricing and investment strategies vary with market structure, the model highlights the policy trade-off between competition and prevention. Second, it provides evidence reversing Arrow's replacement theory in case of public goods: monopolist insurers are more likely to invest in public cost-reduction technology than competitive firms in the insurance industry.

The literature on catastrophe insurance finds evidence of large uninsured risks, but the investment decisions of insurance companies do not target reduction of the insured risks (Bank of England 2015). This literature is focused on pricing climate risks (Oh et al 2023) or finding appropriate contract designs such as parametric insurance to reduce adverse selection and moral hazard (Clarke 2016, Hill et al 2019, Karlan et al 2014). Insurance industries traditionally rely on spreading these risks across regions (Oh et al 2023) or markets through reinsurance. However, there exists an underexplored friction in the context of catastrophe insurance: non-diversifiable risk. Losses from an extreme climate event are likely to arise for multiple policyholders at once which leads to 'lumpy' claims for insurance companies (Molk 2016). In high climate risk areas, traditional property insurers have started withdrawing and are being replaced by lower-quality insurance providers which service riskier policyholders and hold lower capital (Sastry et al 2023). As the risks are close to systematic rather than idiosyncratic, these investments typically require collective action for risk reduction (Kelly et al 2015). Public investments such as resilience infrastructure benefits insurance providers through mitigation of these physical catastrophe risks (OECD 2018). However, these investments are constrained due to competition concerns as well as by the lack of theoretical or empirical guidance on investments by insurance companies to mitigate these risks (Bank of England 2015, Sasson et al 2021). To the best of my knowledge, this paper is the first to model preventive investments in public goods by private insurers and the competitive concerns therein.

The most closely related literature on implications of preventive measures for insurance is in the context of health insurance (Einav and Finkelstein 2011, Finkelstein et al 2012, Dixit 2023). Most papers examine demand-side constraints to low prevention utilisation in health insurance (Dickstien et al 2024). Li (2024) examines the competition concerns in health insurance industry with preventive healthcare. This paper extends this analysis to climate risk, which faces a different set of systemic frictions: non-diversifiable risk in insurance provision and collective action problem in preventive measures with non-exclusionary benefits.

Another related strand of literature studies the effects of industry competition on investments in cost-reduction technology, usually under process innovation (Tirole 1988). We focus on process innovation in the paper, which reflects the gains from preventive investments in the case of insurance. Arrow replacement theory states that the incentives to invest in cost-reduction innovations for monopolies are lower than for competitive firms (Arrow 1962). Empirical evidence is mixed: innovation and competition in the industry are often found to follow an inverted U-shaped pattern, where innovation is lowest in monopolies and highly competitive markets (Aghion et al 2005). In this paper, I show that when the expected cost-reduction technology is a public good, the results of Arrow's replacement theory are reversed. Monopolies are more likely to invest in cost-reduction investments than duopolies under Bertrand competition, as discussed in Section 4.

To present the intuition, I start with a static model of insurance with preventive investment in Section 4. I use the model to examine the trade-off between promoting private infrastructure investments and competition in the insurance market. Next, I simulate a numerical example when monopoly insurers reduce their prices to below competitive prices due to investment. The competition-investment tradeoff extends to the dynamic case, as I argue in Section A where preventive investments and insurance premia respond to the changes in market power.

2 Insurance and Preventive Investments

Natural catastrophe insurance provides protection against catastrophe risks such as earthquakes, floods, cyclones etc. These economic shocks typically hit an entire region at once and this risk is undiversifiable within the region. The primary approach to absorb this risk has been insurance. However, more frequent catastrophes due to increasing climate risk has made underwriting climate insurance very challenging. Reinsurance rates have gone up drastically and traditional insurers have started exiting these markets (Sastry 2023). A potential solution is for insurers to mitigate these climate risks by investing in climate resilience infrastructure. Resilience infrastructure includes green and built infrastructure which enhances the ability to ‘cope, adapt, and transform’ in response to climate change-induced events. For instance, in drought- or flood-prone regions this could include dams and watershed infrastructure or mangroves in cyclone-prone regions. These infrastructure could be small- or large-scale infrastructure which reduce the physical catastrophe risks (OECD 2018) and thus, reduce the expected insurance claim payouts.

The health insurance literature also carefully considers preventive investments for expanding insurance coverage (Einav et al. 2020, Jones et al. 2019, Newhouse 2021). Existing studies focus on demand-side frictions that cause under-investment, such as consumers’ ex-ante moral hazard (Ellis and Manning 2007). Ho and Lee (2017) examine the effect of competition in insurance industry on welfare and prices, by estimating the trade-off between reduced price setting power vs bargaining power with hospitals as a result of competition. Li (2024) provides an equilibrium analysis of how supply-side interactions drive underprovision of preventive measures. In Section A, I extend this analysis to climate risk, which faces a different set of systemic frictions: non-diversifiable risk in insurance provision and collective action problem in preventive measures with non-exclusionary benefits.

A key feature of these preventive investments is that they are typically public goods. As the climate risks are close to systematic rather than idiosyncratic, these investments typically require collective action for risk reduction (Kelly et al 2015). However, these investments are constrained due to competition concerns, arising from collective action problems inherent to public goods. As competition in a market increases

This paper also aims to address market failures which result in lower insurance coverage in climatically vulnerable regions, which has negative multiplier effects through the whole economy. The three market failures are of non-diversifiable climate risk, basis risk, and collective action problem in provision of preventive measures.

First, the friction of non-diversifiable risk limits the feasibility of climate insurance. Traditional property insurers, even in developed insurance markets, have started withdrawing and are being replaced by lower-quality insurance providers which service riskier policyholders and hold lower capital (Sastry et al 2023, Oh et al 2023). Second, climate insurance also carries basis risk (difference between actual and modeled yield loss). A vast majority of the insurance industry is still underwriting current risks on a year-by-year basis (Surminski et al 2016). Preventive investments reduce basis risk by mitigating the insured climate risk. Third, collective action problem for providing this public infrastructure. As all insurers benefit from the preventive investments, which reduce the risk for all policyholders in a given region, they cannot internalise the benefits of investing. Thus, without coordination mechanisms, the insurance companies do not find it optimal to bear the costs of the investment themselves, even though it is pareto-optimal.

Addressing these frictions in climate insurance can lead to an increase in firm and household productivity. Multiple studies show that households respond to natural disasters by reducing consumption and drawing down savings if they do not have collateralizable assets

(Sawada and Shimizutani 2008, Patnaik et al 2019). Thus, insurance payouts and accessible credit could provide timely and localised safety-net for maintaining consumption and savings (World Bank 2017). More broadly, efforts to develop insurance while investing in resilience infrastructure are likely to have spillover effects in multiple sectors of the economy.

3 Preventive Investments and Competition

Arrow (1962) models the incentives for innovation for an individual firm under different market conditions, given patent protection. It shows that the monopolist's 'pure' incentive to innovate is lower than the social planner's as the monopolist cannot fully appropriate the social surplus from cost-reducing innovation. Importantly, monopolist's incentive is also lower than a competitive firm's as the competitive firm gains cost advantage over its rivals to gain monopoly power while the monopolist only 'replaces' herself. Thus, the ratio of incentives to innovate for competitive firm to incentives for monopolist firm is greater than one under the model. We focus on process innovation, i.e. reduced marginal cost of output, to reflect preventive investments in the case of insurance.

The literature on competition and innovation is vast and does not lead to clear theoretical predictions (Gilbert 2006, Shapiro 2011). The ambiguous relationship between market power and investments for innovation arises when dynamics of market power and efficiencies are taken into account. Baker (2007) identifies principle relating higher competition with higher innovation such as synergies towards same new process, preemptive innovation which discourages rivals, and incentives to gain cost advantage over rivals. Schumpeter (1943) holds the opposite view: that prospect of market power and large firms in an oligopoly spurs innovation, rather than small firms in a competitive market. However, these models do agree on the following: there is an inverse relationship between market power and welfare under static analysis (Motta 2004). They state that monopolies lead to static inefficiencies: they charge higher-than-optimal prices and their investments in innovation are lower-than-optimal.I bring this static analysis into question and show that with non-diversifiable risk and publicly available innovation, monopolies can result in lower prices and higher investments.

A key tenet of these models is appropriability of innovation: the innovating firm benefits from a reduced marginal cost from the new technology, which its rivals cannot use. This captures the extent to which a firm can capture the social benefits (positive externality) created by a process innovation. In Arrow (1962), patents of indefinite length protect the process innovations from being appropriated by the firm's rivals. This protection allows a firm to gain cost-advantage in a competitive market, which provides incentives to the firm for innovation (Arrow 1962, Tirole 1988). However, the preventive measures in climate insurance differ from these innovations as there are no protections on appropriability of their benefits, such as patents, as discussed in Section 2. Indeed, this is in line with Schumpeter's thesis that prospect of market power spurs innovation when it allows appropriating its benefits, through patents.

Thus, this framework is not sufficient to study competition concerns in the case of climate insurance. The benefits of these investments are not appropriable by the investor as the innovation (preventive investment) has non-excludable benefits and are public goods. I model this problem in a static analysis and extend the same motivating question in this literature to the present case: to what extent does perfect competition lead to optimal allocation of resources towards public preventive investment. While there are several papers examining competition in insurance markets (Rothschild and Stiglitz 1978, Frank and Lamiraud 2009, Ho and Lee 2017), they do not account for competitive concerns arising from public investments by insurance companies or feasibility concerns with non-diversifiable risk. To the best of my knowledge, this is the first paper to do so.

In the next section, we discuss how provision of these preventive investments, when they are largely public goods, differs widely across competitive conditions in a market. The model shows that monopoly results in an increase in preventive investments, which reduces non-diversifiable risk and increases welfare.

4 Model

I model a firm's decision to invest in a cost-reducing technology, given the competitive nature in the market and the public good nature of the investment. Our thought experiment is to ask how much will the firm invest in a cost-reduction investment, given that the investment reduces the expected costs of all firms in the market. This would allow us to examine different rates of preventive investments across different competitive conditions in the market. We first consider the static version of the problem: how does a single-period insurer optimise her preventive investment and insurance pricing decisions.

Consider the case of two distinct insurance markets with extremal market structures: one is a monopoly and the other is a duopoly with Bertrand price competition. The risk is independent across two markets but is highly correlated within the market, that is the risk is not fully diversifiable across individuals. In the spirit of Arrow (1962), the preventive investments by the insurers lead to a cost-reduction technology (process innovation). However, our key departure from these models is that there are no protections on appropriability of their benefits, such as patents. The preventive investment technology benefits every insurer in a given region, as it is a public good. We show how increased insurer competition has a theoretically ambiguous impact on premiums and investments, when these have non-excludable benefits.

4.1 Setup

The monopolist insurer M faces a market demand $D(P_M)$ at the premium price P_M and pays out claims at the rate θ. The insurer also decides the level of preventive investment, which reduces it's claims rate in the same period for a cost of C_M. The insurance claims rate θ is thus a decreasing function of C_M. The preventive investment influences the demand for insurance only through prices in the model. The monopolist simultaneously chooses a pricing (P_M) and preventive investment (C_M) strategy to maximise her expected payoff:

$$\pi_M = \max_{P_M, C_M \geq 0} \left[P_M - \theta(C_M)\right] D(P_M) - C_M \tag{1}$$

where P_M is the price charged by the monopolist, $\theta(C_M)$ is the claim expenditure and C_M is the expenditure on public preventive measures.

The claims expenditure decreases in preventive investment, i.e. $\theta(C_M)$ is a decreasing function in C_M, $\theta'(C_M) \leq 0$, and $\theta^{''}(C_M) > 0$. I use the most general form of demand function $D(P_M)$, with standard assumptions for profit-maximization: D is a differentiable, decreasing, concave function of insurance price P_M, i.e. $D'(P_M) < 0, D''(P_M) < 0$. Assume that $-\theta'(0)D(P) > 1$, i.e. the marginal benefit of preventive investments at $C = 0$ is higher than its marginal cost. In this static model without time-to-build consideration, these decisions pertain to the same period. An **Equilibrium** in the monopoly market is a set of preventive investments and premia $\{C_M^*, P_M^*\}$ such that $\{C_M^*, P_M^*\}$ maximises insurer profits Π_M in Eq. 1.

Also consider a distinct market with Bertrand price competition with two non-colluding insurers, who provide a homogeneous insurance product. This is the smallest competitive market in equilibrium and serves as a benchmark for decisions under perfect competition. Each duopolist $i \in \{1, 2\}$ simultaneously decides its pricing and investment strategy for the period. Thus, it faces the following optimization problem:

$$\Pi_i^* = \begin{cases} \max_{C_i} \left[P_{iB} - \theta(C_i + C_{-i})\right].s_i D(P_{iB}) - C_i & \text{if } P_{iB} \le P_{-iB} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where (3)

$$s_i = \begin{cases} 1 \text{ if } P_{iB} < P_{-iB} \\ 0 \text{ if } P_{iB} > P_{-iB} \\ \frac{1}{2} \text{ if } P_{iB} = P_{-iB} \end{cases} \tag{4}$$

The profits of insurer i depend on it's choice of insurance premium P_{iB}, the quantity of insurance it sells at the price $s.d_i(P_{iB})$ with its share s of the demand d at the chosen premium, the claims rate $\theta(C_i + C_{-i})$ and the preventive investment expenditure C_i. Let $C = C_i + C_{-i}$ and θ be twice-differentiable in C, with $\theta'(C) \le 0$ and $\theta''(C) > 0$. The fact that preventive investments have non-excludable risk mitigation benefits is reflected in the fact that preventive investment by *any* insurer decreases the claims rate $\theta(C)$ for *each* insurer, where $C = C_i + C_{-i}$.

4.2 Equilibrium

We examine the Nash equilibrium in each market separately and compare how the equilibria outcomes vary across competitive conditions. We begin by characterising the equilibria. Equilibrium in the monopoly market is a set of preventive investments and premia $\{C_M^*, P_M^*\}$ such that $\{C_M^*, P_M^*\}$ maximises insurer profits Π_M in Eq. 1. A Bertrand-Nash Equilibrium in the duopoly market is a set of preventive investments and premia $\{C_1^*, C_2^*, P_{1B}^*, P_{2B}^*\}$ such that $\{C_i^*, P_{iB}^*\}$ maximise insurer profits Π_i in Eq. 2, given $\{C_{-i}^*, P_{-iB}^*\}$.

Lemma 1 *The preventive investment by the monopolist facing the profit maximisation problem in Eq. 1 is strictly positive in Nash Equilibrium.*

The proof of Lemma 1 is straightforward to see. The following necessary first-order condition of Eq. 1 in order for preventive investment C^* to be profit-maximising are:

$$-\theta'(C_M^*)D(P_M) - 1 \leq 0 \text{ with equality if } C_M^* > 0 \tag{5}$$

As $-\theta'(C_M^*)D(P) - 1 > 0$ at $C_M = 0$ by assumption, this condition is only satisfied at $C_M^* > 0$. As $\theta''(C) > 0$, this is the profit maximising level of preventive investment.

Thus, Lemma 1 shows that the monopolist insurer would find it optimal to invest in preventive measures, even when it has non-excludable benefits. This is intuitive due to the fact that there is a single insurer in the market, which is able to internalise all the benefits of its preventive investments. There is also no concern of entry in this static model, which incentivizes the firm to provide the public good [1]. Thus, the monopolist is able to improve upon its own profits before adoption of this technology. We now compare this investment C_M^* to the preventive investment in a competitive market.

Proposition 2 *The Nash equilibrium investment in public preventive measure is higher under monopoly competition given by Eq. 1 (C_M^*) than the combined investment by duopolists under Bertrand-Nash equilibrium given by Eq. 2 (C_1^*, C_2^*).*

$$C_M^* > C_1^* + C_2^*$$

The Proposition 2 is proved in Appendix. Intuitively, in the Bertrand price competition (with no capacity constraints binding the duopolists), each insurer will charge the competitive price in equilibrium, i.e. price will equal the marginal cost. This results in zero profits for the firm and hence, it is not feasible to incur the fixed cost of investment. Thus, while the incentive to invest is the same for a duopolist, as marginal benefits at $C_i = 0$ are greater than marginal cost, competition concerns stop her from incurring the fixed cost.

[1] I briefly discuss why relaxing this restriction on entry in the market would not alter the results, in Section 4.4.

Thus, Proposition 2 shows that in the static setting, monopoly insurance markets result in a higher level of preventive investment than competitive markets, exemplified by Bertrand duopolists. This is due to two reasons: first, firms in low competition markets have a greater incentive to invest in public investments as a greater share of the cost-reduction benefits accrue to them. When there is a high degree of price competition in the market, preventive investments by insurers would be low when they bear the full cost but not the full risk-reduction benefits of the investment. This results in under-provision of preventive investments in the market, even when it is socially optimal to provide them. Second, since these investments incur fixed costs of investments, they are feasible for monopolistic firms with positive profits. Thus, it is both incentive-compatible and feasible for monopolists to invest. As the model shows, the feasibility of bearing these costs disappears with an increase in number of firms in the market.

This result is striking due to its difference from the conventional theory of competition and process innovation: that competitive firms have a higher incentive to invest in cost-reduction than monopolists. In the Arrow (1962) class of models, these investments allow the competitive firms to gain a cost-advantage over their rivals, which allows them to corner the market demand and become a monopolist. Unlike these models where such investment has patent protection, investment in public goods does not allow a firm to gain monopolistic advantage in competitive markets. Hence, the firms in competitive markets do not have an incentive to invest in this setting and their equilibrium investment is zero.

Next, we show that the profit maximising price with preventive investments is lower than the profit maximising price when preventive investments are constrained to zero.

Proposition 3 *Let* (P_M^*) *be the profit maximising price when the monopolist firm invests* C_M^* *by Eq. 1. Let* $P_{M,0}$ *be the profit maximising price when monopoly investments are constrained to be zero, i.e.* $C_M = 0$*. As* $-\theta'(C_M^*)D(P) - 1 > 0$ *at* $C_M = 0$*,* $C_M^* > 0$*. Then,* *when* $D'(P) < 0$ *and* $D''(P) < 0$*, we have that*

$$P_M^* < P_{M,0}$$

and $D(P_M^*) > D(P_{M,0})$.

A sketch the proof is as follows. From the first-order condition of monopolist's profit maximisation in Eq. 5 and $\theta''(C_M) > 0$,

$$C_M^* = g(D(P_M))$$

where g is an increasing function in demand $D(P_M)$ for a profit-maximising firm. As $C_M^* > 0$ by Prop. 2 and demand $D(P)$ is a decreasing function of price P, we have that

$$P_M^*(C_M^*) < P_M(0)$$

Proposition 3 shows that the preventive investments incentivise insurers to expand insurance coverage with a lower insurance premia relative to a case with no such investments. The intuition is that preventive investments create a margin of profit: these investments incur a fixed cost but reduce expected claims per unit of demand serviced. This incentivises the monopolist to increase insurance coverage by reducing the premium and earn yet higher profits (if not, monopolist could have invested at $C_M^* = 0$). Thus the monopolist charges a lower insurance premia relative to a case of no preventive investments. On the other hand, the competitive firm cannot utilise this margin as it's competitor will undercut its prices. This is the classic collective action problem with public goods.

The next natural question is how do monopolist's prices compare with competitive prices? We know that the price in competitive markets are driven down to actuarially-fair prices (prices equal expected marginal claims), because insurers' expected profits are zero. Does investing in preventive investments result in significantly high monopoly prices?

Proposition 4 *Let P_M^* be the profit maximising price when the monopolist firm invests C_M^* by Eq. 1 and the premia under Bertrand-Nash equilibrium given by duopolist's Eq. 2 be P_D^*. Then the markup of monopoly price P_M^* over competitive price P_D^* is bounded above by the inverse of price elasticity of demand at P_M^*:*

$$\frac{P_M^* - P_D^*}{P_M^*} < \frac{1}{|e_D|} < 1 \tag{6}$$

with equilibrium preventive investments $\{C_M^*, 0, 0\}$ and price elasticity of demand at P_M^*, $e_D = \frac{D'(P_M^*)P_M^*}{D(P_M^*)}$.

Proof: The first-order profit maximising condition of the monopolist with respect to P_M is given by

$$\begin{aligned} [P_M^* - \theta(C_M)]D'(P_M^*) + D(P_M^*) &= 0 \\ P_M^* + \frac{D(P_M^*)}{D'(P_M^*)} &= \theta(C_M) \end{aligned} \tag{7}$$

By Proposition 1, we know that $C_M > \theta(C_D) = 0$ and as $\theta'(C) < 0$ for all C. Thus, we have that

$$\begin{aligned} \theta(C_M^*) &< \theta(0) \\ P_M^* + \frac{D(P_M^*)}{D'(P_M^*)} &< \theta(0) \end{aligned}$$

by Eq. 7. Moreover, as $P_D^* = MC(C = 0) = \theta(0)$ for Bertrand duopoly,

$$P_M^* + \frac{D(P_M^*)}{D'(P_M^*)} < P_D^*$$

Thus,

$$P_M^* - P_D^* < -\frac{D(P_M^*)}{D'(P_M^*)}$$

Thus, the difference between monopoly P_M^* *and Bertrand duopoly price* P_D^* *is bounded above by a positive scalar,* $-\frac{D(P_M^*)}{D'(P_M)}$ *which is positive as* $D'(P_M) < 0$ *and* $D(P_M) > 0$ *for all* P_M*. Moreover, this ratio equals the inverse of demand elasticity* e_D *scaled by* P_M^**, thus the price markup between monopoly and Bertrand competitive firm is bounded by:*

$$\begin{aligned} P_M^* - P_D^* &< -\frac{D(P_M^*)}{D'(P_M)} \\ P_M^* - P_D^* &< \frac{P_M^*}{|e_D|} \\ \implies \frac{P_M^* - P_D^*}{P_M^*} &< \frac{1}{|e_D|} \end{aligned}$$

Moreover, the monopoly price elasticity of demand at equilibrium price P_M^* *is more than one. By first order condition of monopolist profit maximisation problem:*

$$\begin{aligned} \frac{\partial \Pi}{\partial P_M} = [P_M^* - \theta(C_M)]D'(P_M^*) + D(P_M^*) &= 0 \\ P_M^* + \frac{D(P_M^*)}{D'(P_M^*)} &= \theta(C_M) \\ 1 - \frac{\theta(C_M)}{P_M^*} &= \frac{1}{|e_D|} \end{aligned}$$

As $\theta(C_M) > 0, P_M^* > 0 \implies 1 - \frac{\theta(C_M)}{P_M^*} < 1$*. Thus,* $\frac{1}{|e_D|} < 1$*.*

This result states that the monopoly price markup over competitive price is bounded above by the inverse of price elasticity of demand, when monopolist invests in preventive investments. For a high price elasticity of demand, the difference between monopoly prices and Bertrand competitive prices would be very small, which signifies welfare gains due to preventive investment in the monopoly markets. Moreover, the monopolist price-setting solution does not lie inelastic part of the demand curve in equilibrium, so the bound remains informative and arbitrarily high monopoly prices are not observed in equilibrium.

Note that the monopoly markup over competitive prices defined in this model (Eq. 6) differs from the monopoly markup in the standard Lerner's Index. The Lerner's Index is based on marginal cost of the monopoly at equilibrium prices, which does not equal marginal cost pricing of the competitive firm:

$$\underbrace{\frac{P_M^* - \theta(0)}{P_M^*}}_{\text{markup over competitive price}} < \underbrace{\frac{P_M^* - \theta(C_M^*)}{P_M^*}}_{Lerner's Index} = \frac{1}{|e_D|}$$

This formulation is informative because it highlights the difference between the marginal costs faced by the competitive and monopoly firms in equilibrium which is driven by the difference in preventive investments by firms in equilibrium.

Thus, Propositions 2 and 4 show that monopolist insurers expand preventive investments with a bounded increase in markup, in absence of competition concerns.

Proposition 4 states that prices under monopoly competition with preventive investment will be lower than Bertrand prices without investment. This seems counter-intuitive to the canonical models, where monopolists charge a higher price for lower quantity in equilibrium to make positive profits. The result in Proposition 4 does not contradict that, as these prices are at different preventive investment levels ($C_M^* > 0, C_B^* = 0$) and hence different marginal costs of output $\theta(C_M^*)$. The competitive price with investment would still be greater than monopolist's price with investment, as noted in Proposition 3. It is also straightforward to see that the monopolist's prices are not actuarially-fair under $\theta(C_M^*)$, as she makes positive profits.

4.3 Welfare

We now consider a social planner's problem for welfare analysis of preventive investments under different competitive conditions. We benchmark the monopolist's allocation in Propositions 2 and 4 against the pareto-optimal allocation and against the competitive market. This analysis allows us to examine the competition-investment trade-off from a welfare perspective and inform policy.

The social planner maximises the net social surplus and hence solves:

$$\Pi_s = (P_s - \theta(C_s))\, D(P_s) - C_s = 0$$
$$\implies P_s = \theta(C_s) + \frac{C_s}{D(P_s)}$$

That is, planner sets insurance price equal to marginal cost after preventive investment, making zero payoff for herself.

Proposition 5 *Preventive investments with a social planner are higher than the equilibrium investment with a monopolist, $C_s^* > C_M^*$. Consumer welfare is also higher with monopolist with preventive investment than with no investment, $CV_s(I_s^*) \geq CV_M(I_M^*) \geq CV_M(0)$.*

Monopolist's price P_M^* is higher than marginal cost with investment, i.e. P_s^* and demand under monopoly prices is lower than under social planner with preventive investment, i.e. $D(P_M^*) \leq D(P_S^*)$. Since g is a increasing function of $D(P)$,

$$g(D(P_M^*)) \leq g(D(P_S^*))$$
$$\implies C_M^* \leq C_S^*$$

Thus, $C_M^* \leq C_S^*$.

The difference in consumer welfare under planner and monopolist is given by:

$$CV_s - CV_M = \int_{P_s^*}^{\infty} D(P)dP - \int_{P_M^*}^{\infty} D(P)dP$$
$$= \int_{P_s^*}^{P_M^*} D(P)dP \geq 0$$

Thus, there is a positive difference between consumer welfare under social planner and under monopolist, which is as expected. Also, as $P_M^* > P_{M,0}$ from Proposition 4 ,

$$\begin{aligned} CV_M - CV_B &= \int_{P_M^*}^{\infty} D(P)dP - \int_{P_{M,0}}^{\infty} D(P)dP \\ &= \int_{P_{M,0}}^{P_M^*} D(P)dP \geq 0 \end{aligned}$$

The final result shows that consumer welfare under monopoly with investment is higher than under price competition which results in no investment. Thus, investment is pareto-improving, even at the cost of welfare loss from reduced competition from allowing monopoly. This pareto-improvement is due to lower prices as well as preventive investments, which an insurer can achieve to increase profits in absence of competition concerns. These results constitute evidence for competition-investment trade-off discussed earlier: decreasing competition in the market results in an increase in preventive investments, which reduces non-diversifiable risk and increases welfare. Thus, even with a simple static model, we have an economic intuition for policy to encourage preventive investments without increasing insurance premia.

4.4 Discussion

The previous section shows that, in the model, monopolist insurers can lower prices as well as expand preventive investments, in absence of competition concerns. This provision is also welfare-enhancing for the consumers relative to a competitive case, which provides no preventive investment. This result is striking due to its difference from the conventional theory of competition and process innovation: that competitive firms have a higher incentive to invest in cost-reduction than monopolists. In the Arrow (1962) class of models, these investments allow the competitive firms to gain a cost-advantage over their rivals, which allows them to corner the market demand and become a monopolist. Unlike these models where such investment has patent protection, investment in public goods does not allow a firm to gain monopolistic advantage in competitive markets. Hence, the firms in competitive markets do not have an incentive to invest in this setting and their equilibrium investment is zero. These results speak to the importance of appropriability for innovation, in line with Schumpeter (1942) hypothesis that large incumbents have a higher incentive to innovate.

The next natural question is of potential entry in the market. The monopolist incurs the fixed cost of the investment if she is assured of her monopoly, i.e. without potential entry into the market. When we consider the dynamic case and potential for competition, the monopolist's investment decision takes into account market entry as well as the effect of investment on future profits, through risk mitigation.

However, the tradeoff between competition and investment for the insurer remains the same as in the static case: the insurer finds it optimal to invest when it can appropriate the benefits of this public good but faced with potential competition, it invests less. Indeed, the investment in public preventive measures is an entry-encouraging investment, as it reduces the expected claims cost for all firms and thus, encourages entry into the market.

This is unlike the canonical market entry models such as Gilbert and Newberry (1982) and Bresnahan and Reiss (1990), where monopoly investments prevent entry into the market. In these models, the monopolist has higher incentive to invest when the benefits are private, as her incentive to maintain the monopoly and prevent entry is higher than a potential entrant's to compete.

Appendix Section A extends the model to the dynamic case with market entry and shows that the results of static model extend to the dynamic one. The monopolist invests in preventive measures to keep current and future costs lower, but it also reduces cost for competitor insurers in the market. This highlights an intertemporal tradeoff faced by the monopolist: investment reduces expected claims for all periods but also reduces market power of the monopolist in subsequent periods, by encouraging entry by potential competitors due to lower costs. Thus, the tradeoff between competition and investment for the insurer remains the same as in the static case.

While there exist multiple equilibria in the generalised model, there exists an equilibrium where the monopolist finds it optimal to make this entry-encouraging investment if the risk-mitigation benefits across periods outweigh the loss from reduction in market power in subsequent periods. Appendix Section A highlights this intertemporal tradeoff between risk mitigation and market power.

5 Numerical Example

Next, we illustrate the model with an example. For this, we simulate the static model numerically with a range of hypothetical parameters to visualize the results and comparative statics of the relevant parameters.

We start by defining the parameters needed to simulate the model:

1. Distribution of expected claims function: we need a distributional form for the expected claims function $\theta(C)$ such that it is a downward-sloping convex function: $\theta'(C) < 0, \theta''(C) > 0$.

2. Demand function: the model admits any general downward-sloping demand curve: $D(P)$ such that $D'(P) < 0$. We have also assumed that the set of efficient investments is not null, as the marginal benefit of investing at $C = 0$ is strictly more than the marginal cost: $-\theta'(0)D(P) > 1$.

While the results described above hold for general functions which satisfy these condition, we need specific functional forms to simulate the above parameters. Thus, we use the following functional forms:

1. Distribution of expected claims function:

$$\theta(C) = a + be^{-kC}$$

   where $a = 10, b = 60, k = 0.05$. A change in expected claims with a unit change in investment is $\theta'(C) = -bke^{-kC} < 0$ for all $C \geq 0$.

2. Demand function: we choose a linear demand function

$$D(P) = \alpha - \beta P$$

with $\alpha = 60, \beta = 1$ in the baseline model. Thus, $D'(P) = -1 < 0$ and

$$-\theta'(0)D(P) = -bke^0(\alpha - \beta P)$$

The condition $-\theta'(0)D(P) > 1$ is satisfied at $P < 40$ for these parameters. Thus, these functional forms satisfy the above-listed conditions and ensure there exists a set of efficient investments.

Figure 1 and 2 visualise the demand function and expected claims function respectively.

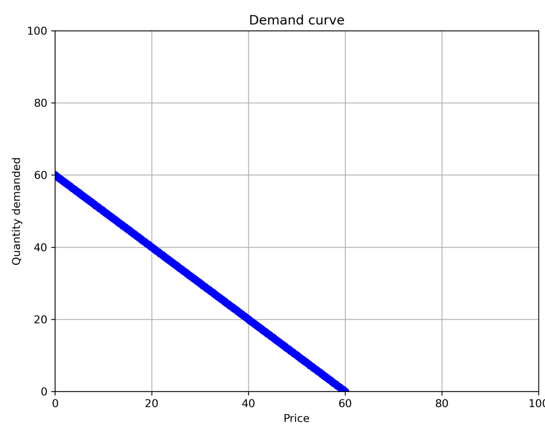

Figure 1: Demand function $D(P) = 60 - P$

These parameters give us a unique profit maximising choice of pricing and investment for the monopoly at $P_M^* = 35.4, C^* = 85.9$. Figure 3 visualises the expected profits for the monopoly as a function of insurance price and investment.

Each firm in the Bertrand duopoly invests $C^* = 0$ and prices insurance at $P = \theta(C)$ (price = marginal cost). Thus, $P_D^* = 70$. Note that $P_D^* > P_M^*$.

Next, we analyse how sensitive these results are to changes in parameter values. Specifi-

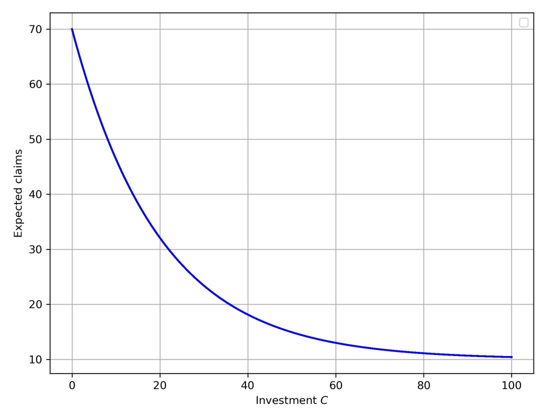

Figure 2: Expected claims function $\theta(C) = e^{-0.05C}$

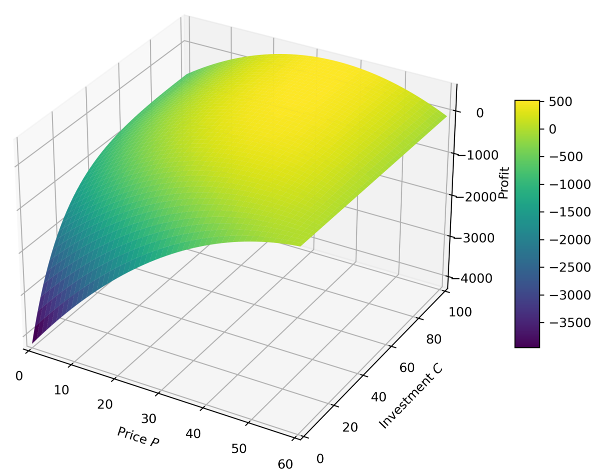

Figure 3: Expected profits as a function of price and investment

cally, we ask how expected profits change with changes in the elasticity of expected claims to investment. The parameter k determines the elasticity of expected claim to changes in investment.

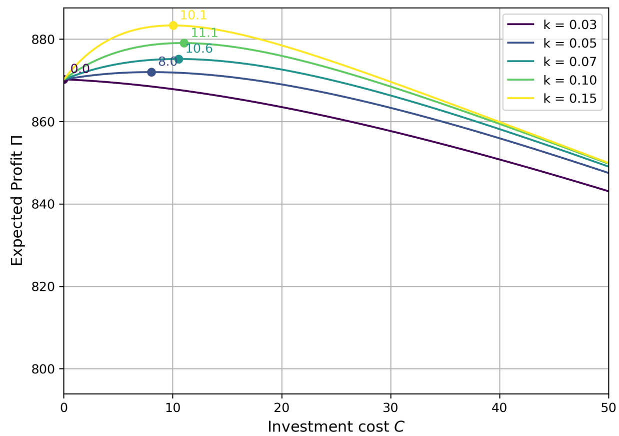

Figure 4: Expected profits and investment at P^*

We plot the expected profits against investment in Figure 3 for different values of k. We see that higher values of k non-linearly changes the optimum investment C^*. This non-linearity is due to the fact that marginal expected profits are non-linear in k:

$$\frac{\partial \Pi_M}{\partial C} = bke^{-kC} - 1$$

If the elasticity of expected claims to investment is very low, the marginal expected profits do not increase at a rate higher than investment costs, which causes the optimal investments to be even zero for low levels of k (eg: $k = 0.03$).

Thus, it is imperative for estimation of the model to have a empirical estimates of this elasticity. However, there are no causal estimates of how natcat insurance claims, or underlying productivity estimates, change with more investments in preventive investments like adaptation infrastructure. Thus, the next step of the project is to estimate elasticity of agricultural productivity from MNREGA policy in India, which builds adaptation infrastructure at a large scale.

6 Conclusion

Traditional methods of risk management, especially insurance, are unable to defray the non-diversifiable risks posed by climate change. Preventive investment by insurance companies is an underexplored mechanism to reduce non-diversifiable risks. Insurance companies under-invest in risk mitigation measures, especially when they are public goods, due to competition concerns, lack of a coordination mechanism, and lack of empirical estimates of their costs and benefits.

Public investment in these preventive measures would be pareto-optimal, as shown in Proposition 3. At the same time, these measures such as resilience infrastructure faces high upfront costs and amortized gains over several decades into the future – a well-known challenge with funding public infrastructure. In such an environment, an already burdened public funds may witness greater pressure for climate adaptation investments, especially in emerging and low-income economies. The lack of climate resilience and public infrastructure sets back the process of structural transformation in vulnerable developing countries. Is there a role for private markets to monetize risk-mitigation benefits from resilience infrastructure? This paper is the first to lay down a theoretical framework for investments by private insurers in public goods under non-diversifiable risk.

The paper shows that first, a monopolist insurer's optimal investment in preventive measures is positive, even when it has non-excludable benefits. This is intiutive due to the fact that there is a single insurer in the market, which is able to internalise all the benefits of its preventive investments. Second, monopoly insurance markets result in a higher level of preventive investment than competitive markets, exemplified by Bertrand duopolists. This result is striking due to its difference from the conventional theory of competition and process innovation: that competitive firms have a higher incentive to invest in cost-reduction than monopolists. Unlike these models where such investment has protection of benefits such as patents, investment in public goods does not allow a firm to gain monopolistic advantage in competitive markets. Hence, the firms in competitive markets do not have an incentive to invest in this setting and their equilibrium investment is zero. Third, the difference between competitive price of insurance and monopoly price with preventive investments is bounded above. For some demand and cost functional forms, this difference could even be negative: that is, monopolist insurer with preventive investment can lower prices below competitive prices without investment. The intuition is that preventive investments create a margin of profit: these investments allow the monopolist to increase insurance coverage by reducing the premium and earn yet higher profits. The competitive firm cannot utilise this margin as it's competitors will undercut its prices. This is the classic collective action problem with public goods. Thus, monopoly with investment is pareto-improving in this case, even with reduced competition. Fourth, consumer welfare under monopoly with investment is higher than under monopoly with no investment.

These results constitute evidence for competition-investment trade-off discussed earlier: decreasing competition in the market results in an increase in preventive investments. Note that there is a trade-off between competition and investments, not welfare and investments as welfare is higher under monopoly. As Motta (2004) succinctly put: 'competition policy is concerned with defending market competition in order to increase welfare, not preserving competitors'. Thus, even with a simple static model, we have an economic intuition for policy to encourage preventive investments without increasing insurance premia.

These results extend to the dynamic case and I show this with a very general, two-period model which accounts for entry decisions of potential competitors.

Next, I plan to estimate the model with data from India, leveraging a public works policy in India, to characterise the equilibrium. I will then use the model to conduct counterfactual policy simulations and evaluate policy alternatives. This would allow more robust analysis of the trade-off between promoting private infrastructure investments and competition in the insurance market.

A Appendix: Dynamic model with market entry

This is a model of insurer investments in preventive measures under competition. The first model was a static model which showed that an insurance firm finds it optimal to invest in preventive investments as a monopolist, but not as a competitive firm in a Bertrand duopoly market. We now want to generalise this result to a dynamic case, as the investment problem is inherently a dynamic one, and consider if the results hold when we have potential market entry in the monopoly market.

Empirically, we have a crop insurance market where there are monopoly firms in most regions. We want to simulate an economy where they would invest in adaptation infrastructure and reduce expected claims. This opens the market up for potential entry by competitors who will profit from reduction in aggregate risk in the market. To match this setting, I develop a model of an incumbent monopolist with investment in public goods and potential market entry.

The other models in related insurance-investment literature are based on multi-firm markets and their estimation is based on empirically estimated market shares. They are also based on individual-level preventive investment with consumer commitment as the primary market friction, like in health insurance literature, while our friction is the non-excludability of the investment. Hence, we write a novel model with an incumbent monopolist, in line with the empirical setting, and simulate equilibrium outcomes with investment in adaptation.

A.1 Model Setup

We use firms' equilibrium payoff functions to describe firms' optimal entry strategies. Consider a sequential market-entry game with two periods. There is an incumbent monopolist firm i in the first stage. The monopolist chooses an investment level I in the first stage, which positively affects her profits in both stages of the game. Let the expected profits of firm i as a monopolist be $\Pi_{it}^{M}(I)$ in stage 1 of the game.

Firm j observes the choice of I and can enter the market in Stage 2 of the game. The entrant j can choose one of two pure strategies: either enter, $E_j = 1$, or do not enter, $E_j = 0$. If she enters, let her expected profits as duopolist in second stage be $\Pi_j^D(I)$, which are increasing in the choice of I by firm i (because I is a public good). The firm i makes a (simultaneous) decision to whether to stay in the market, $E_i = 1$ or $E_i = 0$, and earn $\Pi_{i2}^D(I)$ as a duopolist in stage 2. As the game ends after stage 2, there is no investment by either firm at the stage.

Thus, the lifetime profits of i are

$$\Pi_i(I) = \Pi_{i1}^M(I) + \beta[\Pi_{i2}^D(I).E_j + \Pi_{i2}^M(I).(1 - E_j)].E_i$$

where $\Pi_{i2}(I) = \begin{cases} \Pi_{i2}^M(I) \text{ if } E_j = 0 \\ \Pi_{i2}^D(I) \text{ if } E_j = 1 \end{cases}$

Let firms earn zero profits from the outside option of not entering the market.

As the duopoly profits do not exceed monopoly profits for a given level of investment, we place the restriction:

$$\Pi_k^D(I) \leq \Pi_k^M(I) \tag{8}$$

for $k \in \{i, j\}$ and for all $I \in R_+$. Note that this does not preclude a reversal for a different level of investment, which is a key mechanism for us. For instance, there can exist an I s.t.:

$$\Pi_j^D(I) > \Pi_j^M(I')$$

where $I > I'$.

A.2 Equilibrium

We characterize the Sub-game Perfect Nash Equilibria (SPNE) in pure strategies for the sequential game described above. We start with a general version of profit function as described above, where profits are fully characterized by time, firm and industry competition (monopoly/duopoly). This version is general enough to allow for different characterisation of profit functions (expected profits, profits with minimum capital constraint etc). The aim is to see how far we can get with the general characterisation and it is in the tradition of seminal market entry papers like Gilbert and Newbery (1982) and Bertrand and Reiss (1991).

A.3 Strategies

The pure strategies in SPNE of the two firms are described by the following inequalities:

$$E_i^* = 0, I = I^* \iff (1 - E_j^*)\Pi_{i2}^M(I^*) + E_j^*\Pi_{i2}^D(I^*) < 0,$$

$$\Pi_i(I^*) \geq \Pi_i(I')\forall I' \in R_+$$

$$E_j^* = 0 \iff (1 - E_i^*)\Pi_{j2}^M(I^*) + E_i^*\Pi_{j2}^D(I^*) < 0$$

That is, given the firm i action of $I = I^*$ and $E_i^* = 1$, the firm j chooses to not enter if her duopoly profits $\Pi_{j2}^D(I^*) < 0$. If $E_i^* = 0$, the firm j chooses to not enter if her monopoly profits $\Pi_j^M(I^*) < 0$. Similarly, given the entry decision E_j of firm j, firm i chooses not to stay in the market in the second period if her profits are negative.

We want to see what happens to investment by a monopolist, when there is potential competition. Does the monopolist invest in preventive measures, when this investment encourages market entry by competitors? To focus on the interesting cases, let us consider equilibria under the following restriction: investment at any small positive level makes it feasible for the firm j to enter (this is generalizable to any positive investment):

$$\Pi_j^D(I) \geq 0 \text{ for all } I > 0$$

There are multiple pure-strategy sub-game perfect equilibira in this game: an equilibrium where neither firm invests nor stays in the market in second stage, incumbent stays in market without investment, and one where an incumbent invests and competitor enters the market in second stage. We characterize these equilibria below in Sections A.4 and A.5 and we focus on the interesting case of duopoly market with investment in Section A.6, as it represents a case of entry-encouraging investment.

A.4 SPNE I: No market and no investment

The following equations give us the condition for the first Sub-game perfect Nash Equilibrium (SPNE): $E_j^* = 0, E_i^* = 0, I^* = 0$.

$$\Pi_i^M(I) > 0 > \Pi_i^D(I) \forall I > 0 \tag{9}$$

$$\Pi_j^D(I) > 0 > \Pi_j^M(0) \forall I > 0 \tag{10}$$

Intuition by backward induction: in the second stage, the firm i does not want to invest because if it invests any $I > 0$, firm j would enter (by eq. 10) and this will result in negative profits for firm i (by eq. 9). Thus, in first stage, the firm i anticipates this and does not invest. It also does not stay in the market in the second stage as $0 > \Pi_i^M(0)$. Thus, $E_j^* = 0, E_i^* = 0, I^* = 0$.

A.5 SPNE II: Monopoly with no investment

The strategies $\{E_j^* = 0, E_i^* = 1, I^* = 0\}$ describe a sub-game perfect Nash equilibrium where the incumbent monopolist does not invest in the first period and stays in the market in the next period, while the firm j does not enter. This equilibrium exists when:

$$\Pi_{i1}^{M}(I') + \beta\Pi_{i2}^{D}(I') \leq \Pi_{i1}^{M}(0) + \beta\Pi_{i2}^{M}(0)$$
$$\Pi_{j}^{D}(0) \leq 0$$

for all $I' > 0$.

A.6 SPNE III: Entry-encouraging investment

As $\Pi_{j2}^{D}(I) \geq 0$ for all positive investment, the entrant chooses to enter the market for any positive investment. Given that the best response of entrant is to enter the market for any positive investment ($E_j^* = 1$), the monopolist invests in $I^* > 0$ when:

$$\Pi_{i1}^{M}(I^*) + \beta\Pi_{i2}^{D}(I^*) \geq \Pi_{i1}^{M}(0) + \beta\Pi_{i2}^{M}(0)$$

That is, the best response of the monopolist is to invest I^* when the total profits from investment as a duopolist in the second period are more than being a monopolist with no investment. This holds when:

$$\Pi_{i1}^{M}(I^*) - \Pi_{i1}^{M}(0) \geq \beta[\Pi_{i2}^{M}(0) - \Pi_{i2}^{D}(I^*)]$$
$$\Pi_{i1}^{M}(I^*) - \Pi_{i1}^{M}(0) \geq \beta[\Pi_{i2}^{M}(0) - (\Pi_{i2}^{D}(0) + \epsilon)]$$
$$\underbrace{\Pi_{i1}^{M}(I^*) - \Pi_{i1}^{M}(0) + \beta\epsilon}_{\text{risk mitigation benefit}} \geq \beta\underbrace{(\Pi_{i2}^{M}(0) - \Pi_{i2}^{D}(0))}_{\text{loss in market power}}$$

where $\epsilon = \Pi_{i2}^{D}(I^*) - \Pi_{i2}^{D}(0)$.

This characterisation represents the inter-temporal risk mitigation- market power tradeoff which the monopolist faces: investment in preventive measures reduces expected claims through investment in all periods, but this increases the incentives for market entry by competitors which results in the monopolist losing market power in subsequent periods. Here, $\Pi_{i1}^{M}(I^*) - \Pi_{i1}^{M}(0)$ is the risk-mitigation benefit from investment in the first period, which is under a monopoly market, and $\beta\epsilon = \beta(Pi_{i2}^{D}(I^*) - \Pi_{i2}^{D}(0))$ is the discounted risk-mitigation benefit from investment in the second period, which is under duopoly market power.

This also represents a case of entry-encouraging investment by a monopolist in equilibrium, as investments into preventive measures by a monopolist do not deter entry by potential entrants. On the contrary, these investments encourage entry by potential entrants as they reduce the expected claims for them and make it more feasible to underwrite insurance in the market.

Thus, these results are unlike usual market entry models like Gilbert and Newbery (1982) and Bertrand and Reiss (1991) where investments by a monopolist are higher under potential market entry as they preempt entry and help the firm retain market power. On the other hand, investments in public goods do not preempt entry, as they have non-appropriable benefits and reduce the expected claims for all potential entrants and thus, encourage entry in the market.

B Appendix: Proofs

B.1 Proof of Proposition 2

In the competitive market, each firm solves the following problem: it first decides the profit-maximising level of preventive investment with fixed cost C_i which results in a marginal cost function $\theta(C_i + C_{-i})$, given the other firm's best response C_{-i}. In the second stage, each firm simultaneously chooses the prices. In this model without time-to-build consideration, these decisions pertain to the same period. As is standard in Bertrand price competition in a homogeneous good market, the firm which charges a lower price meets all the market demand. Thus, each firm charges the competitive premium price equal to it's marginal cost of insurance:

$$P_B = \theta(C_i + C_{-i})$$

Each competitive firm makes zero profits. The profit-maximization problem of the duopolist insurer i with price P_B and share s of market demand $D(P_B)$ gives:

$$\Pi_i = \begin{cases} \max_{C_i} \left[P_{iB} - \theta(C_i + C_{-i})\right].s_i D(P_{iB}) - C_i & \text{if } P_{iB} \leq P_{-iB} \\ 0 & \text{otherwise} \end{cases}$$

Thus, both firms set prices at the marginal cost $P_{iB} = \theta(C)$, where $C = C_i + C_{-i}$

$$\begin{aligned} \Pi_i &= 0.s_i D(P_B) - C_i \\ &= -C_i \end{aligned}$$

Thus, each duopolist i will find it optimal to invest $C_i^* = 0$. This is the Nash equilibrium as neither has an incentive to deviate from $C_i^* = 0$. To see why, suppose that is not the case. Without loss of generality, firm 1 deviates to $C_1 > 0$ and reduces its claims cost by $\theta'(C_1)$. Due to public goods nature of the investment and non-diversifiable insured risk, this investment also reduced claims cost for firm 2, without incurring any cost. The minimum prices feasible for firm 1 are such that $(P_{1B} - \theta(C_1))sD(P_{1B}) - C_1 = 0$. However, firm 2 can undercut with $P_{2B} < P_{1B}$ and corner all the market demand, i.e. $s = 1$. Anticipating this, firm 1 would lower its C_1 until $C_1^* = 0$, which is the lower bound. Thus, in Nash Equilirbium, $C_1^* = C_2^* = 0$.

As $C_M^* > 0$ by Lemma 1, we see that $C_M^* > C_1^* + C_2^* = 0$.

B.2 Proof of Proposition 3

The monopolist profit-maximisation problem is:

$$\pi_M = \max \; (P_M - \theta(C_M))\, D(P_M) - C_M$$

where $\theta'(C_M) \leq 0$ and $\theta''(C_M) > 0$. Thus, the monopolist faces the following first-order condition with respect to preventive investment, C:

$$-\theta'(C_M)D(P_M^*) = 1$$

As $\theta''(C_M) > 0$,

$$C_M^* = g(D(P_M^*))$$

where g is an increasing function in demand $D(P_M^*)$. Thus, as $C_M^* \geq 0$

$$\implies D(P_{M,0}) \leq D(P_M^*)$$
$$P_{M,0} \geq P_M^*$$

B.3 Proof of Proposition 4

The first-order profit maximising condition of the monopolist with respect to P_M is given by

$$[P_M^* - \theta(C_M)]D'(P_M^*) + D(P_M^*) = 0$$
$$P_M^* + \frac{D(P_M^*)}{D'(P_M^*)} = \theta(C_M) \tag{11}$$

By Proposition 1, we know that $C_M > \theta(C_D) = 0$ and as $\theta'(C) < 0$ for all C. Thus, we have that

$$\theta(C_M) < \theta(0)$$

By Eq. 11,

$$P_M^* + \frac{D(P_M^*)}{D'(P_M^*)} < \theta(0)$$

Moreover, as $P_D^* = MC(C = 0) = \theta(0)$ for Bertrand duopoly,

$$P_M^* + \frac{D(P_M^*)}{D'(P_M^*)} < P_D^*$$

Thus,

$$P_M^* - P_D^* < -\frac{D(P_M^*)}{D'(P_M^*)}$$

Thus, the difference between monopoly P_M^* and Bertrand duopoly price P_D^* is bounded above by a positive scalar, $-\frac{D(P_M^*)}{D'(P_M)}$ which is positive as $D'(P_M) < 0$ and $D(P_M) > 0$ for all P_M. Moreover, this ratio equals the inverse of demand elasticity e_D scaled by P_M^*, thus the price markup between monopoly and Bertrand competitive firm is bounded by:

$$P_M^* - P_D^* < -\frac{D(P_M^*)}{D'(P_M)} = \frac{P_M^*}{|e_D|}$$

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