

# Natural Disasters, Land-Use, and Insurance\*

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August 31, 2016

## Abstract

This paper addresses the urbanization of areas exposed to natural disasters and studies its dependency on land-use and insurance policies. The risk-map paradox that we describe explains why an insurance system with simplistic maps and tariffs is the rule. Indeed, in practice we observe simple policies, consisting of a prohibited red zone and a zone without insurance tariff differentiation. We show that they implement the optimal land-use in specific cases. Even if there are fixed damages per dwelling, the red-zone policy is relatively efficient. In a central proposition, we detail the effects redefining the optimal red zone as the climate or the population changes. We use this analysis to expose and comment plausible cases in which, as the population grows, the red zone shrinks, the red zone grows, and the red zone shrinks and then grows.

*Keywords:* natural disasters, insurance, land-use regulation, climate change

*JEL classification:* G22, R52, Q54

## 1 Introduction

The economic costs of natural disasters have risen dramatically over the last decades (BEVERE et al. 2015, Figure 4, page 6). The increase is largely explained by the growing number of people and businesses located in exposed areas and the value of their assets (BARREDO 2009; BEVERE et al. 2011). Many areas that are exposed to catastrophic risks are indeed inhabited and used for economic activities. In China, 50% of the population lives in the 8% of the land area located in the mid- and downstream parts of the country's seven major flood-prone rivers; they contribute over two-thirds of the total agricultural and industrial product value (ZHANG 2004). In Florida, in 2012,

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\*The authors thank Nicolas Grislain, Frédéric Loss, Erwann Michel-Kerjan, and Marion Oury for their comments on the text. They also thank Stephen Coate for his help on public assistance, Valérie Sanseverino-Godfrin for explanations about law and legal precedents, and Cédric Peinturier and Clément Lenoble for explanations about risk engineering. This paper has benefited from comments by participants at the CREST internal seminars, the University Paris-Dauphine research day, the ETH Zurich and University of Nantes seminars, the Symposium on France-Taiwan Frontiers of Science and the World Risk and Insurance Economics Congress. This study was supported by the FIME Research Initiative, the Chair Finance and Sustainable Development, and the Fondation du Risque.

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80%, or \$2.9 trillion, of the insured assets were located near the coasts, the highest risk areas in the state (AIRWORLDWIDE 2013). Globally, the world's coastal areas concentrate a large and growing population in many of the world's largest cities (HALLEGATTE et al. 2013).

This growing urbanization in exposed areas is favored by the fact that households who settle in the exposed areas do not bear the full cost of the risk they take, either because they expect the community to provide assistance or because of a poorly designed discriminatory pricing of their coverage. This is an example of moral hazard. Other plausible reasons for this density could be ignorance, perception biases, or the positive amenities of these risky areas (landscape in mountainous or coastal areas, commercial activities near rivers). Our focus is on the fact that people who settle in the exposed areas do not pay for the risk they take; and we limit our scope to the non-life losses from these disasters.

The solution to control urbanization in exposed areas combines land-use and insurance policies. The theoretical power and practical limitations of these policies form the key focus of our analysis. Land-use policies lead sometimes to strong actions. For example, since the Great Flood of 1993 in the United States, the Federal Emergency Management Agency has acquired nearly 4,500 flood-prone homes in the state of Missouri;<sup>1</sup> entire towns, such as Valmeyer, Illinois, have also moved from the floodplain to higher ground (BAGSTAD et al. 2007). Insurance policies can also limit free-riding by making households and businesses located in exposed areas pay for the risk they take. For example, the earthquake insurance premiums in Japan or the flood insurance premiums in the United States increase with respect to the risk exposure (TSUBOKAWA 2004; KOUSKY and MICHEL-KERJAN 2010). However, even in these cases, the premium increase is regulated. In Japan, there are only four earthquake premium zones, which correspond to those delineated by the Probabilistic Seismic Hazard Maps (TSUBOKAWA 2004). In the United States flood insurance premiums are subsidized for exposed houses that were built before the risk maps; this subsidy reduces the expected flood losses and increases the demand for high-risk coastal living beyond what would occur in a free market, as highlighted in Santa Rosa County (Florida) by MORGAN (2007).

To show how land-use regulations and insurance premiums contribute to shaping equilibrium risk exposure, we develop an urban model of a linear city with a significant risk gradient, where we endogenize the land rents, insurance premiums, and location choices. The outer limit of the territory is given; a possible example is a valley bordered by a river bed and a crest. We assume that the hazard reduction measures, such as dams or levees, are fixed.

In principle, insurance premiums and land-use regulations are equally powerful: insurance premiums can achieve a Pareto optimum via prices, whereas zoning directly controls land-use. The equivalence goes further because premiums and zoning are substitutes on any scale. If an

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<sup>1</sup>Federal Emergency Management Agency, "Nearly 5,000 Missouri Families Made Safer Since 1993 Floods." March 28, 2008. See [link](#).

area, big or small, is treated as uniform by insurance firms, then the degrees of efficiency can be gained with zoning restrictions. If, in contrast, an area has a uniform zoning regulation despite the heterogeneity of risk, then the differentiation in the insurance premiums can compensate for the imperfection in the zoning. Ultimately, the land use is jointly determined by the insurance premiums and by the zoning regulations.<sup>2</sup>

We claim that coarse tariffs and regulations are worth examining as practical second-best solutions. First, risk maps are not socially optimal, because they are public goods that improve risk management and the design of incentives, and the provision of public goods is often inefficient. Second, fine risk discrimination (either for insurance or land-use) is politically infeasible. Flat tariffs are undermined by cream skimming, which may leave uninsured a worrying fraction of the most exposed population, except if insurance is mandatory, or at least heavily regulated. Fine land-use regulations are also hardly accepted: suspicion on the objectivity of the recommendations easily arises, because the expertise is highly concentrated. These two facts constitute the risk-map paradox: the insurance and land-use policies are never as good as the risk maps they rely on, and these maps are not as precise as they should be in the first place.

We thoroughly investigate the most commonly used two-zone policy. In the red zone, dwellings are prohibited, and in the building zone, authorized density and insurance premiums are location-blind. Location-blind premiums have two interpretations. The first is implicit insurance, namely assistance expected from the state in case of disaster. In many European countries such as Germany, Italy, or Poland, flood compensation relies on state-funded assistance schemes.<sup>3</sup> The second is nondiscriminatory insurance pricing, such as in Denmark, France, Spain, or Switzerland, where natural disasters insurance is location-blind. This second scheme is often the modernization of the first. Indeed, in many countries, natural disaster coverage is based on compulsory location-blind contributions via state-funded assistance schemes or insurance systems that institutionalize and coordinate former aid mechanisms (DUMAS et al. 2005).<sup>4</sup> In most countries, this inefficient pricing is accompanied with building prohibition. In France, Germany, Italy, Poland, Spain, and Switzerland, there is binding legislation with respect to restricting or prohibiting the development of flood-prone areas (SANTATO 2013). Red zones summarize the trade-offs encountered by decision-makers: extending the region where building is forbidden reduces the total cost of risk and crowds households at the same time.

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<sup>2</sup>See MCDONALD and MCMILLEN (2012) for a discussion about the economics of zoning and their practical feasibility compared with Pigouvian taxes.

<sup>3</sup>See GRISLAIN-LETRÉMY and LEMOYNE DE FORGES (2014) for a review of the numerous countries where flood compensation relies on compulsory location-blind contributions either via state-funded assistance schemes or via insurance systems.

<sup>4</sup>In France and in Spain for example, location-blind insurance is organized by the government and comes automatically with basic property insurance policies (DUMAS et al. 2005). The French natural disaster insurance system was created in 1982 to institutionalize and coordinate numerous aid mechanisms that had lasted for centuries (FAVIER and LARHRA 2007); in Spain, coverage of extreme risks was first organized after the Civil War (1936-1939) and was later extended to other extraordinary risks, including natural disasters (CONSORCIO DE COMPENSACIÓN DE SEGUROS 2008).

We show that this red-zone policy is optimal as long as the potential losses are proportional to the surface used. Even if there are fixed damages per dwelling, the red-zone policy is relatively efficient. In terms of analysis, this policy is amenable to comparative statics.

Updating the zoning as risk changes is crucial. A key contribution of our work is the determination of the impacts of climate change and demographic pressure on optimal red zones. Currently the increasing cost of natural disasters is largely explained by the growing urbanization in exposed areas. Climate change might be beginning to contribute to this trend for certain regions and hazards (KOUSKY 2014). In the future it is expected to have a major impact. The European Parliament and the Intergovernmental Panel on Climate Change indeed argue that climate change will increase the intensity and the frequency of natural disasters (ANDERSON 2006; SCHNEIDER et al. 2007). Global flood damage for large coastal cities will increase eightfold between 2005 and 2050, with projections based only on increasing population and property value. Once climate change and subsidence are added, global flood damage for large coastal cities could increase 19-fold and cost \$1 trillion a year if prevention is not upgraded (HALLEGATTE et al. 2013).

We identify the three distinct effects that determine the net impact of climate change or demographic pressure on the red zone. The risk-intensification effect is the direct increase of risk due to climate change or demographic pressure. The risk-sharing effect is its consequences on households' incomes and derived demand for land. The land-sharing effect is the direct increased demand for land due to demographic pressure. As intuition suggests, a higher disaster frequency or seriousness causes an extension of the red zone. In contrast, a population increase raises the risk but increases the demand for land at the same time. The net impact of demographic pressure can be a reduction (respectively an extension) in the red zone when expected damages per head are deemed negligible (respectively dominant) compared to expected damages per surface units. These effects are discussed in detail in the general case, and we illustrate them with parametric examples and simulations. Our approach is similar to the one taken in our article studying industrial risks (GRISLAIN-LETRÉMY and VILLENEUVE 2016). Part of the problem lies in the durability of housing and the large up-front payments that must be made in order to move residents out of hazardous areas relative to the benefits that are realized only with low probability. Our analysis does not solve this issue but it shows where it is particularly acute.

Several papers cover the management of natural disasters. In a model derived from the classical urban economics literature (see FUJITA and THISSE 2002, for a review), FRAME (1998) takes into account a second spatial dimension: locations not only vary in terms of distance to the center, but also in terms of risk. The paper proposes comparative statics on the equilibrium variables for each of two cases: where households have to absorb their losses by themselves and where actuarially fair insurance (including loading) is available. We analyze instead the combination of suboptimal insurance and land-use regulation, and its comparative statics. We assume away commuting costs,

whose effect is well documented in the literature. Though the total cost of living somewhere (risk plus transportation) can be nonmonotonic, we can reorder positions in increasing order of total cost of living to justify our simplification.

FRAME (2001) shows that starting from a situation without insurance or with imperfect insurance (for example because of loading), a small dose of location-blind coverage increases welfare. The reasoning is that making exposed areas more desirable benefits everyone through the alleviation of urban congestion. In fact, his result is local: complete location-blind insurance might not Pareto dominate the absence of insurance, because it unleashes urbanization in exposed areas. Our objective is precisely to analyze the complementary policies that counteract this undesirable effect.

In our approach, as in Frame's, insurance fully covers the losses, and risk influences the location choices only through the insurance premium, which makes cognitive biases on risk perception irrelevant.<sup>5</sup> This is not to deny the practical importance of cognitive biases, but rather to propose a basic and pure analysis of the common types of real world institutions. The empirical works confirm that housing markets value the capitalized flow of natural disaster insurance premiums (BIN et al. 2008; MACDONALD et al. 1990; HARRISON et al. 2001; NYCE et al. 2015) and that insurance rates can significantly modify real estate markets.<sup>6</sup> Real estate prices respond even more to insurance premiums than to any other risk revelations: in Houston (Texas), real estate prices did not immediately decline after the 1979 flood, but once flood insurance premiums rose sharply one year later, they did (SKANTZ and STRICKLAND 1987).

PICARD (2008) proposes a model in which households' locations are fixed and they differ with respect to their exposure to natural disasters. Actuarially fair insurance is efficient because it induces consumers to optimally invest in prevention and mitigation. However, inequalities are inevitably attached to the individualized rates; for that reason, transfers between agents are used. Combining actuarially fair insurance with transfers Pareto dominates location-blind insurance, which ensures equity but is inefficient. In this paper, we examine competitive location choices and therefore adopt an orthogonal long-term perspective. Transition is another major challenge: how to move people if the risk increases? Long-term targets such as those we study provide guidelines.

The paper continues as follows: Section 2 presents the model. Section 3 characterizes the performance of the optimal red zone policy. Section 4 details the impact of climate change and demographic evolution on the size of the red zone. Section 6 concludes.

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<sup>5</sup>TATANO et al. (2004) recall that correcting imperfect risk perception could enhance market efficiency.

<sup>6</sup>See NYCE et al. (2015) for a review.

## 2 Model

### 2.1 Households, space, and risk

**Households.** We assume a continuum of identical households. Their utility  $U(z, s)$  depends on their consumption  $z$  of the composite good (henceforth money) and on their housing size  $s$ ; they have no intrinsic preference for one location over another.  $U$  is twice differentiable and strictly increases with respect to  $z > 0$  and  $s > 0$ . The indifference curves are strictly convex and do not cut axes in the relevant domain.<sup>7</sup>

We denote by  $MRS_{sz}$  the marginal rate of substitution of  $s$  for  $z$ , that is

$$MRS_{sz} := \frac{\partial U / \partial s}{\partial U / \partial z}. \quad (1)$$

The  $MRS_{zs}$  is the reciprocal. We assume that the Engel curves increase:

$$\begin{aligned} \forall(z, s), \quad \frac{\partial MRS_{zs}}{\partial z} &:= \frac{\partial}{\partial z} \left( \frac{\partial U / \partial z}{\partial U / \partial s} \right) \leq 0, \\ \forall(z, s), \quad \frac{\partial MRS_{sz}}{\partial s} &:= \frac{\partial}{\partial s} \left( \frac{\partial U / \partial s}{\partial U / \partial z} \right) \leq 0. \end{aligned} \quad (2)$$

These two assumptions simply say that the relative value of the commodity becoming more abundant decreases; they are simple ordinal sufficient conditions to have increasing Engel curves.

The households are price takers, with  $r$  the rent and 1 the normalized price of  $z$ ; they have a basic income  $\omega$ , and they maximize their expected utility under their budget constraint.

**Space and risk.**  $[0; X]$  is the space of inhabitable locations (Figure 1). The risk source (e.g., the river bed) is located at 0. The distance  $x$  between the source and a location determines the risk exposure. The safest place  $X$  can be seen as a crest. We assume that the hazard reduction measures, such as dams or levees, are fixed.

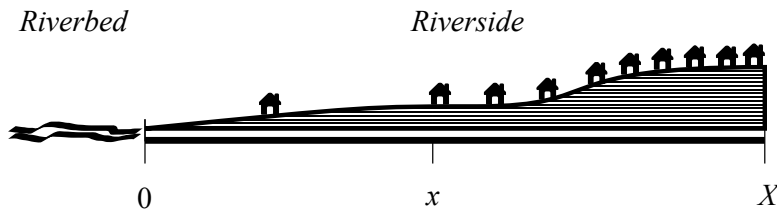


Figure 1: Space and risk. Section view of a riverbed

We assume away commuting costs, whose effect is well documented in the literature. Though the total cost of living somewhere (risk plus transportation) can be nonmonotonic with respect to

<sup>7</sup>Similar to Assumption 2.1 in FUJITA (1989).

$x$ , we can order positions by total cost of living. Strictly speaking, this simple mathematical trick is valid because there are no local externalities (like people caring somehow about their neighbors).

A household lives at a given location, say  $x$ , in  $[0; X]$ ; its dwelling occupies a lot size  $s(x)$ , and the density of households at location  $x$  is  $n(x)$ , so their demand for space is  $n(x)s(x)$  locally. Supply is normalized to 1 if the rent is strictly positive and 0 otherwise, therefore equilibrium of supply and demand implies

$$n(x) s(x) = 1 \quad (3)$$

wherever the rent is strictly positive. The total population is  $N$ .

A dwelling located at  $x$  is damaged with probability  $p(x)$  with

$$\forall x, p(x) := \rho f(x), \quad (4)$$

where the function  $f(\cdot)$  is positive, strictly decreases along the space line, and is piecewise continuous;  $\rho > 0$  is a magnitude index that we use for the comparative statics. The damage per dwelling of size  $s$  is  $\lambda_F + \lambda_S s$ ; the first part  $\lambda_F \geq 0$  is fixed and the other part is  $\lambda_S s$  with  $\lambda_S \geq 0$  and is proportional to the house's size. The damage corresponds to the (re)building cost and does not depend on the land's value. There is no damage to empty places.

The expected damage for a dwelling of size  $s$  at location  $x$  is

$$p(x) (\lambda_F + \lambda_S s). \quad (5)$$

This specification in terms of expected damages embeds several interesting features already mentioned in GRISLAIN-LETRÉMY and VILLENEUVE (2016). (1) The risks are spatially correlated. In the case of floods, if location  $x$  is reached, then location  $x'$  with  $0 < x' < x$  is also reached. This fact justifies that the function  $p(\cdot)$  decreases. (2) Over a given portion of the territory, the damages increase with the number of dwellings, and with the occupied surface. These two distinct effects, the relative strength of which is determined by  $\lambda_F$  and  $\lambda_S$  respectively, explain the variety of impacts we discuss in Section 4. More households in the same space mean more potential damages via  $\lambda_F$ ; the demographic pressure changes the surface-related damages via  $\lambda_S$ . (3) An increase of  $\rho$  parametrizes the increase of frequency or intensity of natural disasters due to climate change. It can be seen as a higher probability; over the time period considered,  $p(x)$  can also be seen as the expected number of events, rather than the probability of a single event. An increase of  $\rho$ , which increases  $p(x) (\lambda_F + \lambda_S s)$ , can also be seen as an aggravation of the consequences. Indeed, an alternative natural representation of the risk is to have a common probability  $p$  of disaster, but a decreasing intensity  $i(x)$ . The damage is then of the form  $i(x)(\lambda_F + \lambda_S s)$ . The product  $p \cdot i(x)$  plays the same role as  $p(x)$  for the spatial correlation.



## 2.2 Efficient policies and the risk-map paradox

**Efficient policies and the first-best allocation.** Ideally, the competitive insurance policies would fully cover a dwelling of size  $s$  located at  $x$  for a premium  $p(x)$  ( $\lambda_F + \lambda_S s$ ). The reimbursement would be complete:  $\lambda_F + \lambda_S s$ . This actuarially fair pricing provides the right incentives and would implement a first-best allocation of people in the risky space. The first-best allocations can be described qualitatively. They are based on a non uniform density of the population: the density of population may be null in a non trivial zone along the riverbed; it increases smoothly as one gets farther away from the river. Appendix A.1 characterizes the equilibrium under actuarially fair insurance. The technical proof of efficiency and existence of this equilibrium borrows on the techniques usually employed in urban economics; it is available as Supplemental material to be published on the web.

A Pareto optimal outcome could also be reached with a location-dependent limitation of the population density instead of a location-dependent insurance premium. The density limitation could be implemented through the auctions of the occupancy rights. In practice these discriminatory insurance or land-use policies are rarely implemented.

**The risk-map paradox and the relevance of second-best solutions.** Indeed, insurance or land-use regulations are generally based on location-blind insurance and elementary zoning, or at best on a very small number of zones with differentiated tariffs or differentiated density limitations, as exemplified in Section 1.

Our first proposition is a non mathematical one.

**Proposition 1** (Risk-map paradox).

1. *Risk maps are not socially optimal.*
2. *Zoning used for regulation is much simpler than risk maps could allow.*

*Proof.* 1. Actual risk maps are not perfect: budgets and experts have their limits; updates are rare and slow. Besides, they are unlikely to be optimal because they are public goods that improve risk management and the design of incentives; their provision by the private insurance industry alone is unlikely to be efficient.

2. The insurance and land-use regulations cannot be better than the risk maps they rely on. They are generally worse. Maps on which insurance tariffs and land-use regulations are based are simplistic compared to the scientific knowledge the society as a whole has regarding risks. The reason is that precise maps could lead to extreme discrimination, which is generally not accepted by the public. If highly exposed households had to pay actuarial



premiums, they would not buy insurance or insurers would practice cream skimming, and exposed households would seek and find political support for subsidies, public programs, or anti-discrimination regulations. A stable and frequently observed solution is to impose limited discrimination (depending on the degree of discrimination that the public accepts) plus obligation to accept all customers to avoid the exclusion of extreme risks.<sup>8</sup> Fine density regulations (as the first-best choice would request) are also hard to defend: the expertise is highly concentrated and suspicion on the objectivity of the recommendations can easily arise. A practical (and political) consequence is that zoning ends up much simpler than it could be.

□

However, some risk maps produced by the private sector can be more accurate than the ones produced by the public one, as shown by MICHEL-KERJAN et al. (2015) in the US.<sup>9</sup> But we claim that the private sector is not a secure provider of disaster insurance and underlying risk maps. There are two causes for that market failure, one is the availability or the cost of reinsurance (the causes of that particular phenomenon would require a full analysis); another is cream skimming, which in the long run leaves uninsured a worrying fraction of the most exposed population.

### 2.3 Simple policies and their implications

**Red zones and location-blind insurance.** Simple land-use restrictions partially correct the imperfect internalization of risk and increase efficiency. The most commonly used policy is the “red zone” policy: a red zone where land-use is prohibited and another zone where a location-blind insurance premium is applied. In equilibrium,  $\bar{x}$  denotes both the size of the red zone and the leftmost inhabited location (Figure 2).

The location-blind insurance refers to coverage based on compulsory contributions implemented in many countries, either via state-funded assistance schemes or via insurance systems.<sup>10</sup> In the building zone, the location-blind premium takes the size  $s$  into account, but not the location

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<sup>8</sup>The anti-discrimination argument is powerful political argument. Its ethical value is more dubious (FLEURBAEY and MANIQUET 2012): many people have chosen to live in risk areas, all the more so because they are protected by the society. This protection is a historical fact, but not necessarily a right, and certainly not a fundamental one.

<sup>9</sup>MICHEL-KERJAN et al. (2015) show significant differences when they compare risk-based premiums for storm surge or inland flooding in the United States using commercially developed probabilistic catastrophe models, with the premiums based on the Flood Insurance Rate Maps (delineated by the Federal Emergency Management Agency). They show that the commercial maps are clearly better in terms of incentives and actuarial balance.

<sup>10</sup>COATE (1995) rightly argues that the equivalence between state-funded assistance and insurance is less than perfect. First, the ex post assistance by the state is less efficient because assistance might rely on approximate loss assessments or discretionary decisions. Second, natural disaster assistance is provided by various actors (non-profit organizations, states); so the uninsured can free-ride. We leave these differences aside.

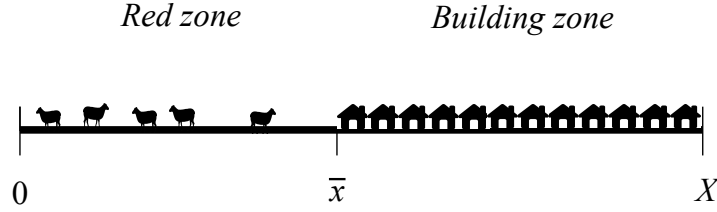


Figure 2: Red zone

$x$  as such. It has two components, one fixed and the other proportional to size:

$$\pi = \pi_F + \pi_S s, \text{ for some } \pi_F, \pi_S > 0 \text{ and for } x \in [\bar{x}, X]. \quad (6)$$

**Land occupation and rent.** A location-blind premium implies free-riding: households do not pay for the risk they generate by locating in exposed areas. In equilibrium, all of the permitted locations have the same value for households, and the building zone is fully and uniformly used. Thus,

$$\begin{cases} s(x) = \frac{X-\bar{x}}{N} = \frac{1}{n(x)} & \text{if } x \in [\bar{x}, X], \\ s(x) = 0 \text{ and } n(x) = 0 & \text{otherwise.} \end{cases} \quad (7)$$

The rent  $r$  is the price per unit at location  $x$ . In equilibrium, in the building zone the rent is uniform, as are the premium and the occupation.

We assume that all of the land is owned by a fund of which households have equal shares. This structure makes sure that any reforms have an identical effect on each household. The households each receive an additional revenue  $R$  that they take as given:

$$R := \frac{X - \bar{x}}{N} r. \quad (8)$$

We use this equation to analyze the income effects.<sup>11</sup>

**Cost of risk.** Within a given community, natural disasters are by nature highly correlated. Yet the number of communities on a much larger scale makes the global risk tolerance high. The insurance can be seen as provided either by an efficient administration or by a perfectly competitive private sector. In the case of public provision, the insurance scheme could be equivalently implemented by a tax. We assume that the insurance sector is risk neutral and without administrative costs.

<sup>11</sup>To find valid results under the “absentee landlord” hypothesis, which is often encountered in the literature, our model can be applied with a quasilinear utility function.

With uniform land-use over the inhabited area  $[\bar{x}, X]$ , the total expected cost of the risk (CR) amounts to

$$\begin{aligned} \text{CR}(\bar{x}) &:= \left( \frac{N\lambda_F}{X - \bar{x}} + \lambda_S \right) \int_{\bar{x}}^X p(t) dt \\ &= (N\lambda_F + \lambda_S(X - \bar{x})) \bar{p}(\bar{x}), \end{aligned} \quad (9)$$

where  $\bar{p}(\bar{x})$  is the average probability in the building zone.

Increasing  $\bar{x}$  decreases the cost of the risk (people occupy less risky zones): the increase leads to a positive marginal risk reduction (MRR).

$$\text{MRR}(\bar{x}) := -\frac{d\text{CR}}{d\bar{x}} \geq 0. \quad (10)$$

We assume that the cost of the risk  $\text{CR}(\cdot)$  is convex, i.e.

$$\forall x, \frac{d\text{MRR}}{dx} \leq 0. \quad (11)$$

A sufficient condition for Equation (11) is a convex  $p(\cdot)$ .

## 2.4 Equilibrium

Given the red zone  $\bar{x}$ , the following variables are determined in the equilibrium: the rent  $r$ , the additional land revenue  $R$ , and the insurance premium parameters  $\pi_F$  and  $\pi_S$ . An equilibrium is a quadruple of numbers  $(r, R, \pi_F, \pi_S)$  such that

1. Households maximize their utilities. Because insurance is complete, the expected utility  $EU$  is nothing other than the utility  $U$ . The households' choice  $(x, z, s)$  solves

$$\max_{x, z, s} U(z, s) \quad \text{s.t.} \quad \omega + \mathcal{K} \geq z + \mathcal{A} + \pi_F + \pi_S s, \quad (12)$$

2. All rents are redistributed equally:  $R = sr$  as shown by Equation (8).
3. The location-blind premium distributes the total expected cost of risk equally between the households:

$$\pi_F + \pi_S \frac{X - \bar{x}}{N} = \frac{\text{CR}(\bar{x})}{N}. \quad (13)$$

There are three equations for four unknowns, the indeterminacy coming from  $\pi_F$  and  $\pi_S$  in Equation (13). All solutions are economically equivalent because households pay exactly the same premium.

### 3 Performance of red zones

#### 3.1 The optimal red zone

The red zone is the only variable that policy can change to reach an optimum in this second-best environment: increasing  $\bar{x}$  reduces the cost of risk and the available space at the same time. The optimal red zone is the solution of the program maximizing households' utility under their budget constraint:

$$\begin{cases} \max_x & U\left(\omega - \frac{CR(x)}{N}, \frac{X-x}{N}\right), \\ \text{s.t.} & 0 \leq x \leq X. \end{cases} \quad (14)$$

**Proposition 2.** *The optimal red zone  $\bar{x}^*$  is the unique solution  $\bar{x}$  of the first-order condition:*

$$\begin{cases} \bar{x}^* = 0 & \text{and } MRR(0) \leq MRS_{sz}\left(\omega - \frac{CR(0)}{N}, \frac{X}{N}\right) & \text{or} \\ \bar{x}^* \in (0, X) & \text{and } MRR(\bar{x}^*) = MRS_{sz}\left(\omega - \frac{CR(\bar{x}^*)}{N}, \frac{X-\bar{x}^*}{N}\right) & \text{or} \\ \bar{x}^* = X & \text{and } MRR(X) \geq MRS_{sz}\left(\omega - \frac{CR(X)}{N}, 0\right). \end{cases} \quad (15)$$

*Proof.* The program (14) is strictly quasiconcave in  $x$ . The Kuhn-Tucker conditions can be rearranged to give the necessary and sufficient condition that defines the unique constrained optimum. Corner solutions are included.  $\square$

The utility of all is  $U\left(\omega - \frac{CR(\bar{x}^*)}{N}, \frac{X-\bar{x}^*}{N}\right)$ . This utility increases with respect to the income  $\omega$  and decreases with respect to the loss parameters  $\lambda_F$ ,  $\lambda_S$ , and  $\rho$ . The impact of an increase in the population  $N$  on the utility is ambiguous: it reduces the lot size occupied by each household but the reduction means a bigger population to share the lot-size-related cost of the risk.

#### 3.2 Efficiency of red zones

The expected cost of risk depends on the number of people via the fixed part of damages,  $\lambda_F$ , and the surface they occupy via the surface-related part,  $\lambda_S$ .

**Proposition 3.** *If the fixed part of damages is null ( $\lambda_F = 0$ ), then restricting the size of the inhabitable area can achieve a Pareto optimum.*

*Proof.* If the fixed part of risk is null, the number of people in the risky areas does not matter for cost minimization – only the occupied area. Thus, defining a red zone where land-use is prohibited can achieve a Pareto optimum.  $\square$

Even in the case where there are fixed damages per dwelling, the simulations in this subsection show that the red-zone policy can be relatively efficient. They are based on a Cobb-Douglas utility function and a linear loss probability,  $U(z, s) = \log(z) + \alpha \log(s)$  and  $p(x) = \rho \cdot (X - x)$ , with  $X = 1, \lambda_F = 1, \lambda_S = 1, \alpha = 1, \omega = 1.5, \rho = 1, N = 1$ .

**Land occupation.** Figure 3 shows a simulation of the equilibrium under location-blind insurance with the optimal red zone (solid line). For comparison purpose, we also draw the simulation of the first-best equilibrium with actuarially fair pricing (dashed line), which can be solved numerically only. The algorithm uses the characterization of the optimum we present in the Appendix A.1 (Muth-Mills condition) and the supplemental material.

Whereas location-blind premiums lead to uniform use of the whole authorized space, actuarially fair insurance provides incentives for households to locate in less risky areas, leading to lower density in riskier areas (Section 2.2 and Appendix A.1). Under actuarially fair insurance, the riskiest areas are spontaneously deserted:  $\bar{x}_{\text{Actuarial}}^* = 0.263$ . This zone is smaller than the optimal red zone which is  $\bar{x}^* = 0.279$ : actuarially fair premiums enable better and more extensive land occupation.

**Welfare.** Simulations show that the optimal red zone can perform well. Figure 4 shows equilibrium utilities. The utility in the first-best equilibrium with an actuarially fair pricing is given by the horizontal dashed line ( $-0.441$ ). The utility with location-blind rates and a red zone is given as a function of the size of the red zone (solid line). The optimal red zone has relatively good performance ( $-0.455$  in Figure 4). To better understand this value, we calculate the compensating variations, that is, the percentage of their initial income people would require to abandon actuarially fair premiums and have location-blind premiums and a red zone instead (Figure 5). This percentage is worth 0.85% for the optimal red zone. This value suggests that a simple red zone policy can perform well even if the fixed part of the damages  $\lambda_F$  is not negligible. This compensation is much higher either for a null red zone (8.96%), because the households are reluctant to pay for the high risk cost, or for a red zone twice as large as the optimal one (17.4%), because the households are not readily willing to reduce so much their land occupation.

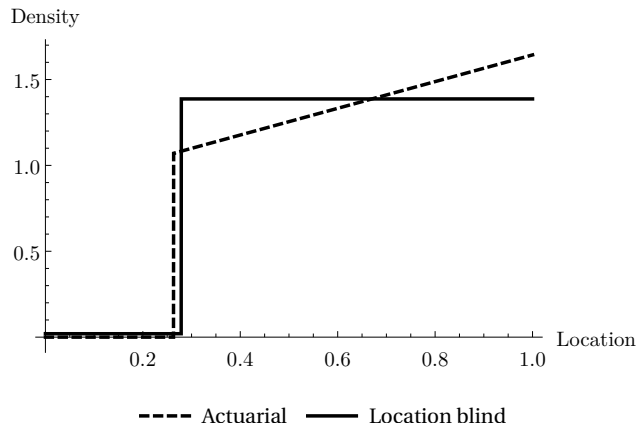


Figure 3: Equilibriums: actuarially fair premiums vs. location-blind premium and optimal red zone.

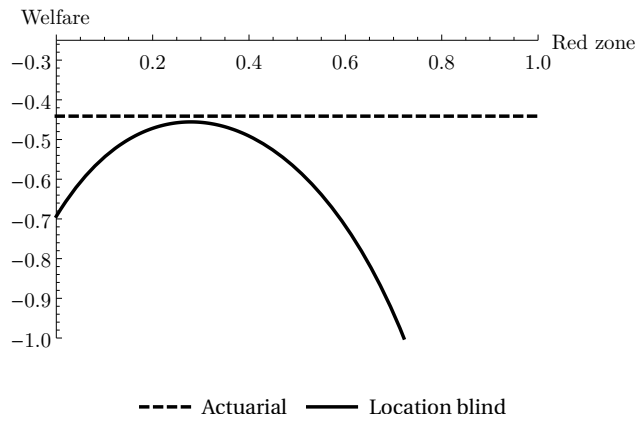


Figure 4: The cost of inefficiency.

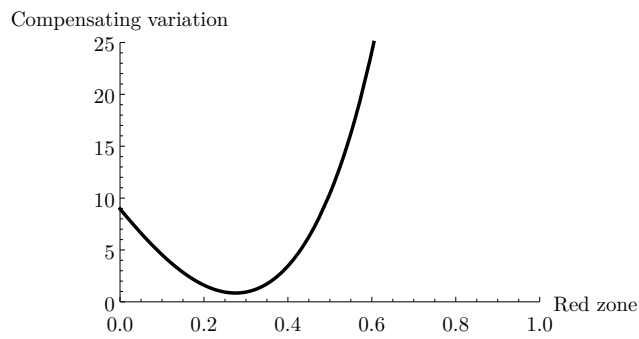


Figure 5: Compensating variation (as a percentage of initial income).

## 4 Climate change, demographic evolution, and zoning update

### 4.1 Updates matter

Risk maps are criticized not only for their lack of precision but also for their obsolescence. The risk-map paradox we unraveled in Subsection 2 explains the former problem, not the latter. As illustrated for the US by MICHEL-KERJAN et al. (2015), maps provided by the public sector need serious regular updates.

Updating is all the more important that climate change and demographic pressure redefine the optimum. Climate change, inasmuch as it increases the frequency and intensity of floods, pushes towards larger exclusion zones. For example, the Netherlands are particularly vulnerable to a rise in the sea level because about 70% of its properties lie below either the current sea level or the river water level (KOK 2003). In 2008, anticipation of climate change effects led the Delta Committee to recommend several advances in water management, including land purchases along the major river areas. The “Room for the River” program, for which over €16bn has already committed for flood defences up to 2028, has implemented such land purchases.<sup>12</sup> In contrast, a population increase raises the risk but increases the demand for land at the same time. Its overall impact on the size of the red zones depends on factors we can analyze parametrically.

We determine the impact of climate change, summarized by  $\rho$ , and demographic evolution, summarized by  $N$ , on the optimal red zone. Insofar as the expected loss can be formally assimilated with transportation costs, PINES and SADKA (1986) establish similar comparative statics for the empty zone: the empty space increases with respect to  $\rho$  and can increase or decrease with respect to  $N$ . We identify here the competing effects that determine the red zone in the second-best situation of location-blind premiums. We first analyze the general case of these comparative statics and then present four complementary calculable examples.

### 4.2 The general case: three key economic effects

For a given red zone  $\bar{x}$ , define  $z(\bar{x}) := \omega - \frac{CR(\bar{x})}{N}$  and  $s(\bar{x}) := \frac{X-\bar{x}}{N}$ , i.e., what is actually consumed. The optimal red zone is characterized by the equality of the marginal risk reduction and the marginal rate of substitution of households between lot size and money (Proposition 2):

$$\text{MRR}(\bar{x}^*) = \text{MRS}_{sz}(z(\bar{x}^*), s(\bar{x}^*)). \quad (16)$$

We focus on interior solutions for simplicity. Thanks to the envelope condition, the impacts of the risk factor  $\rho$  or  $N$  on the optimal red zone are measured by calculating the *direct* impact of the risk factor on the MRR and MRS. We first interpret the three key economic effects at stake.

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<sup>12</sup>The Guardian, May 19th, 2014. [Link](#).



**1. The risk-intensification effect (RIE)** measures the sensitivity of the cost of the risk to the risk factor and pushes for an extension of the red zone.

- The RIE of  $\rho$  depends on both  $\lambda_F$  (per capita share of damage) and  $\lambda_S$  (lot-size-related share of damage):

$$\text{RIE of } \rho := \left. \frac{\partial \text{MRR}}{\partial \rho} \right|_{\bar{x}^*} = \frac{\text{MRR}}{\rho} \geq 0. \quad (17)$$

- The RIE of  $N$  is proportional to  $\lambda_F$ :

$$\text{RIE of } N := \left. \frac{\partial \text{MRR}}{\partial N} \right|_{\bar{x}^*} = \frac{\lambda_F}{X - \bar{x}^*} (p(\bar{x}^*) - \bar{p}(\bar{x}^*)) \geq 0 \quad (18)$$

Thus, if  $\lambda_F$  is negligible, the RIE is dominated by the other effects, and the red zone shrinks.

**2. The risk-sharing effect (RSE)** denotes the evolution of the cost of the risk borne by households that makes them either richer or poorer. This effect modifies the marginal rate of substitution of the households and therefore their demand for land. The sign of this effect varies.

- An increase in  $\rho$  impoverishes the households because they bear the additional cost of the risk, and it reduces their demand for the land. This RSE depends on both  $\lambda_F$  and  $\lambda_S$ .

$$\text{RSE of } \rho := - \frac{\partial \text{MRS}_{sz}}{\partial z} \cdot \left. \frac{\partial z}{\partial \rho} \right|_{\bar{x}^*} \geq 0 \quad \text{as} \quad \left. \frac{\partial z}{\partial \rho} \right|_{\bar{x}^*} = - \frac{\text{CR}(\bar{x}^*)}{N\rho} \leq 0. \quad (19)$$

- In contrast, an increase in  $N$  enriches households because it makes them more numerous in sharing the lot-size-related cost of the risk. Here, this RSE is proportional to  $\lambda_S$ .

$$\text{RSE of } N := - \frac{\partial \text{MRS}_{sz}}{\partial z} \cdot \left. \frac{\partial z}{\partial N} \right|_{\bar{x}^*} \leq 0 \quad \text{as} \quad \left. \frac{\partial z}{\partial N} \right|_{\bar{x}^*} = \frac{\lambda_S}{N^2} (X - \bar{x}^*) \bar{p}(\bar{x}^*) \geq 0. \quad (20)$$

**3. In the case of demographic pressure, the land-sharing effect (LSE)** is the increased demand for land that tends to narrow the red zone.

$$\text{LSE of } N := - \frac{\partial \text{MRS}_{sz}}{\partial s} \cdot \left. \frac{\partial s}{\partial N} \right|_{\bar{x}^*} \leq 0 \quad \text{where} \quad \left. \frac{\partial s}{\partial N} \right|_{\bar{x}^*} = - \frac{X - \bar{x}^*}{N^2} \leq 0. \quad (21)$$

We can now derive the proposition.

**Proposition 4.** *Under technical assumptions (11) on risk and (2) on preferences,*

1. *A higher disaster frequency or seriousness expands the optimal red zone, as the sign of  $d\bar{x}^*/d\rho$  is the sign of*

$$\text{Risk-intensification effect of } \rho (\geq 0) + \text{Risk-sharing effect of } \rho (\geq 0).$$

2. A population increase can pull both ways. Indeed, the sign of  $d\bar{x}^*/dN$  is the sign of

$$\begin{aligned} & \text{Risk-intensification effect of } N (\geq 0) + \text{Risk-sharing effect of } N (\leq 0) \\ & + \text{Land-sharing effect of } N (\leq 0). \end{aligned}$$

*Proof.* See Appendix A.2. □

As intuition suggests, climate change leads to an extension of the red zone. In contrast, demographic pressure raises the risk but increases the demand for land at the same time. The decisive effect is the risk-sharing effect, which is proportional to  $\lambda_S$ : in terms of purchasing power, the individual benefit from having more people is big when  $\lambda_S$  is big. As the risk-intensification effect is proportional to  $\lambda_F$ , so the net impact depends ultimately on the ratio  $\lambda_F/\lambda_S$ , plus the utility function. The net impact of demographic pressure can be a reduction (respectively an extension) in the red zone when expected damages per head are small (respectively dominant) compared to expected damages per surface units.

## 5 Examples

Our examples have been constructed to illustrate the various cases predicted by the general theory regarding the impact of demographic pressure. The first two examples provide the most natural intuition one can have: the optimal red zone  $\bar{x}^*$  decreases with respect to  $N$ . The third and the fourth examples shows that the effect of  $N$  can be reversed or nonmonotonic.

These examples also illustrate the possibilities of sanctuaries. In the first two examples, the increase of disaster frequency may shrink the inhabited region to nothing: there is no *city core*, that is no preserved space for households as  $\rho$  tends to infinity ( $\lim_{\rho \rightarrow +\infty} \bar{x}^* = X$ ) and households are forced onto the crest  $X$ . Conversely, as the population increases unrestrictedly, a *risk sanctuary*, that is a hard red zone, can be preserved ( $\lim_{N \rightarrow +\infty} \bar{x}^* > 0$ ); or can completely vanish ( $\lim_{N \rightarrow +\infty} \bar{x}^* = 0$ ). All these effects are tightly related to the value people give to land in their utility functions.

### 5.1 Specification and solving

We illustrate the interest of our decomposition with simple contrasted examples where (i) the three effects can be calculated and (ii) the optimal red zone can be calculated explicitly so that a conclusion can be warranted.

We take additively separable utility functions of the form

$$U(z, s) = u(z) + \alpha v(s), \tag{22}$$

where  $u$  and  $v$  are either logarithmic or linear, and a linear loss probability

$$p(x) = \rho \cdot (X - x). \quad (23)$$

Assuming an interior solution,<sup>13</sup> the red zone  $\bar{x}^*$  can be calculated from the first-order condition given by Proposition 2:

$$\begin{aligned} \text{"lin-log"} \quad U(z, s) = z + \alpha \log(s) : \quad \bar{x}^* &= X - \frac{1}{4} \frac{\lambda_F}{\lambda_S} N \left( \sqrt{1 + \frac{16\alpha\lambda_S}{N\rho\lambda_F^2}} - 1 \right), \\ \text{"log-log"} \quad U(z, s) = \log(z) + \alpha \log(s) : \quad \bar{x}^* &= X - \frac{1+\alpha}{2(2+\alpha)} \frac{\lambda_F}{\lambda_S} N \left( \sqrt{1 + 8 \frac{(2+\alpha)}{(1+\alpha)^2} \frac{\lambda_S\alpha\omega}{\lambda_F^2 N\rho}} - 1 \right), \\ \text{"log-lin"} \quad U(z, s) = \log(z) + \alpha s : \quad \bar{x}^* &= X + \left( \frac{1}{\alpha} + \frac{1}{2} \frac{\lambda_F}{\lambda_S} \right) N - \sqrt{\frac{\lambda_F^2 N^2}{4\lambda_S^2} + \frac{N^2}{\alpha^2} + \frac{2\omega N}{\rho\lambda_S}}, \\ \text{"linear"} \quad U(z, s) = z + \alpha s : \quad \bar{x}^* &= X - \frac{\alpha}{\rho\lambda_S} + \frac{1}{2} \frac{\lambda_F}{\lambda_S} N. \end{aligned} \quad (24)$$

## 5.2 Effect of $\rho$

In all cases, the red zone increases with respect to  $\rho$ , as predicted by Proposition 4 and illustrated by graphs in Figure 6. These graphs are all drawn with the following parameters

$$X = 1, \quad \lambda_F = 1, \quad \lambda_S = 1, \quad \alpha = 1, \quad \omega = 1.5. \quad (25)$$

A large  $\rho$  implies a probability of disaster larger than 1: given that it commands the loss expectancy, an interpretation is that there are multiple occurrences within the same period (Section 2).

**Limits.** In all cases, there is no city core, that is no preserved space for households as the number of disasters tends to infinity:

$$\lim_{\rho \rightarrow +\infty} \bar{x}^* = X. \quad (26)$$

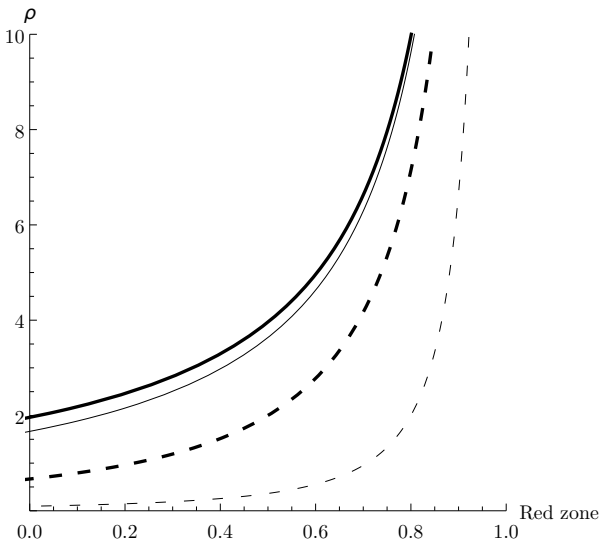
All households tend to be forced onto the crest. This limit is not reached in the first two examples and it is reached for a finite  $\rho$  in the last two.

## 5.3 Effect of $N$

The graphs in Figure 7 show the diversity of possibilities.

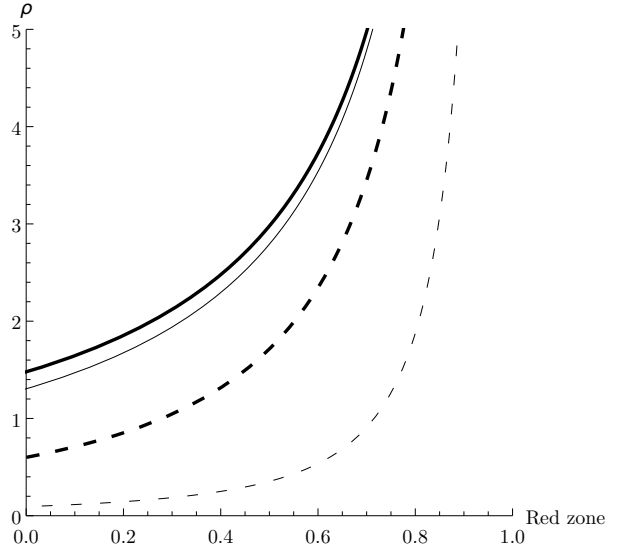
In the first two cases,  $\bar{x}^*$  decreases with respect to  $N$ . Indeed, in the case of the lin-log utility function, the land-sharing effect of Proposition 4 dominates: more people just want more space (Table 1). In the case of the log-log utility function, the sum of the land-sharing effect and the risk-sharing effect dominates the risk-intensification effect.

<sup>13</sup>Strictly speaking the red zone is  $\max\{0, \min\{\text{Interior expression of solution}, X\}\}$ . Assuming an interior solution is without loss of insight.



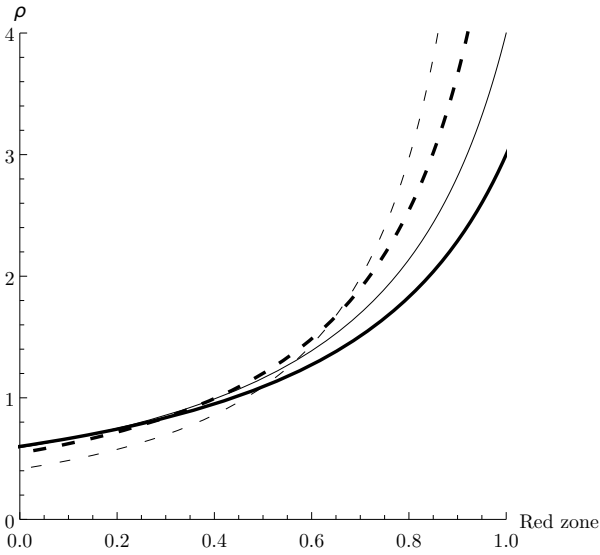
-- N = 0.1    - - N = 1    — N = 10    — N = 100

Linear-log utility function



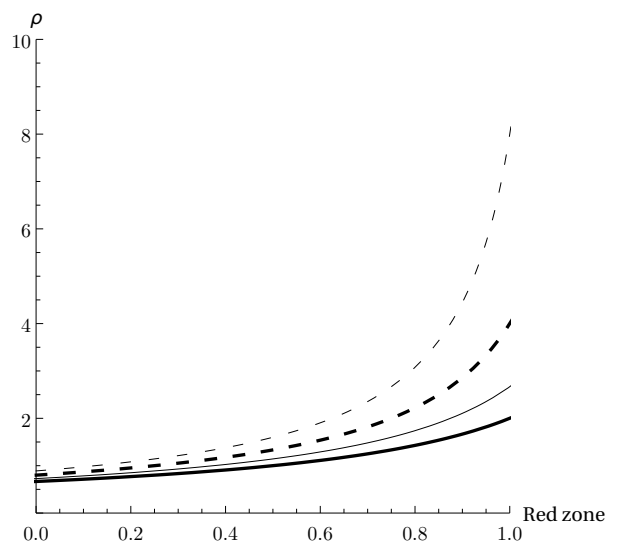
-- N = 0.1    - - N = 1    — N = 10    — N = 100

Log-log utility function



-- N = 0.25    - - N = 0.5    — N = 0.75    — N = 1

Log-linear utility function



-- N = 0.25    - - N = 0.5    — N = 0.75    — N = 1

Linear utility function

Figure 6: Red zone as a function of  $\rho$ .

But contrary to what intuition may suggest, the effect of  $N$  is not monotonic in general, as illustrated by the log-lin utility case. The risk-sharing effect pushes in the opposite direction of the risk-intensification effect as far as  $N$  is concerned (Proposition 4). In the log-lin utility case, the land-sharing effect is null: the marginal value people give to the surface doesn't depend on the surface they actually occupy, meaning that they tolerate well being squeezed. The consequence is that, when they are more numerous, they prefer money (given by the reduction of the cost of risk) rather than the conservation of their occupied space. In this utility case, the derivative  $\partial \bar{x}^* / \partial N$  changes its sign at

$$\frac{2(\alpha\lambda_F + 2\lambda_S)\alpha\omega\sqrt{\alpha\lambda_F\lambda_S} - 4\alpha^2\omega\lambda_F\lambda_S}{\alpha^2\rho\lambda_F^3 + 4\rho\lambda_F\lambda_S^2}. \quad (27)$$

If this value is negative, then the red zone increases with respect to  $N$ . But, as Figure 7 illustrates, this value can be positive, and the red zone is nonmonotonic with respect to  $N$  over  $\mathbb{R}^+$ . For example, for  $\rho = 0.5$ , the red zone starts at  $X$  for  $N = 0$ , then it decreases and stays at 0 over an interval, and finally the red zone increases as  $N$  increases until it reaches  $X$ .

In the linear utility case, increasing  $N$  always decreases the red zone. This is a limit case among additively separable functions where the risk-sharing effect and the land-sharing effect are both null; yet it reveals the importance of preferences in the optimal setting.

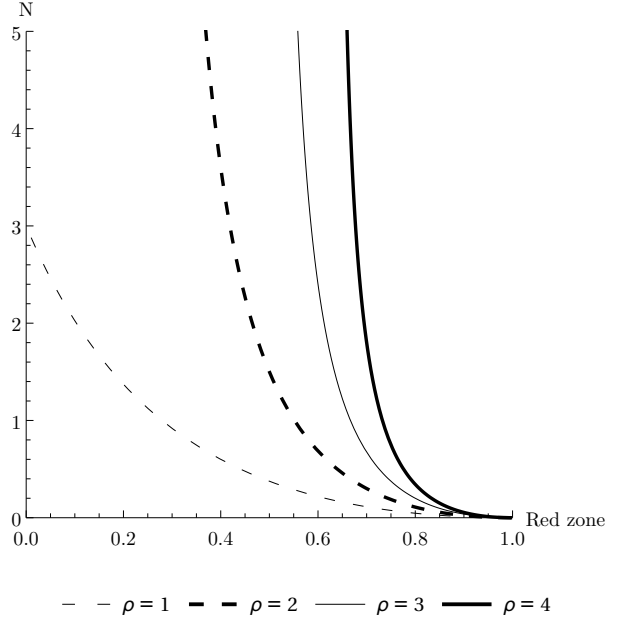
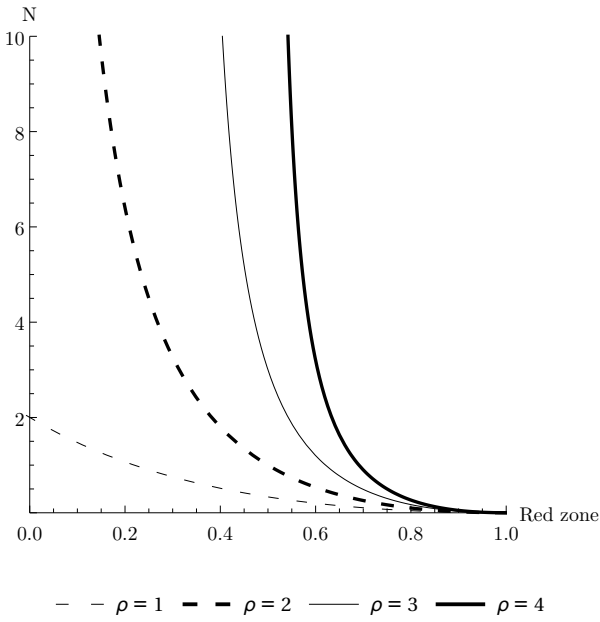
Utility function	RIE	RSE	LSE	Variations of the red zone
"lin-log":	+	0	-	↘
"log-log":	+	-	-	↘
"log-lin":	+	-	0	↘ ↗
"linear":	+	0	0	↗

Table 1: Effect of  $N$

### Limits.

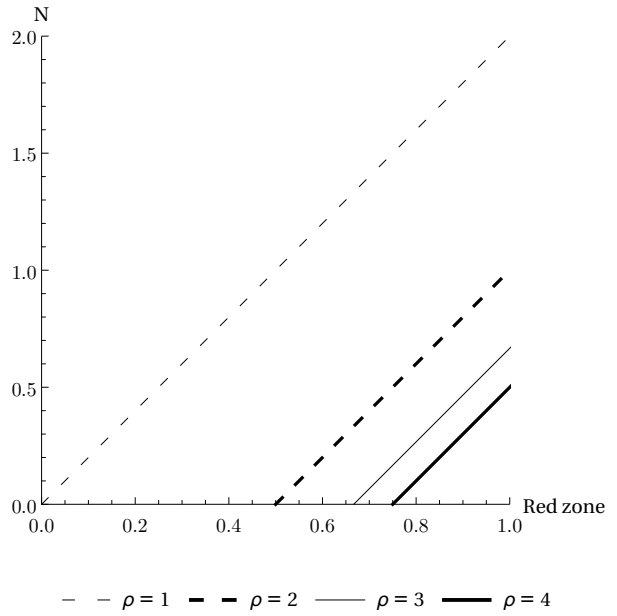
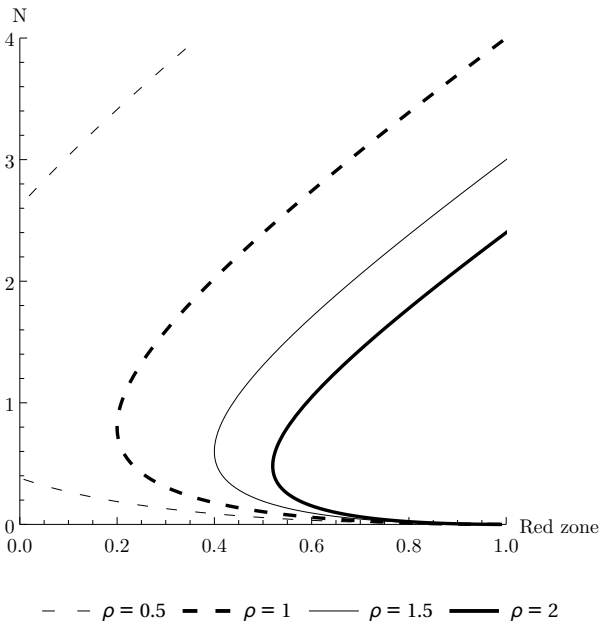
$$\begin{aligned} \text{"lin-log"} : \lim_{N \rightarrow +\infty} \bar{x}^* &= \max \left\{ X - \frac{2\alpha}{\rho\lambda_F}; 0 \right\}, \\ \text{"log-log"} : \lim_{N \rightarrow +\infty} \bar{x}^* &= \max \left\{ X - \frac{2\alpha}{1+\alpha} \frac{\omega}{\rho\lambda_F}; 0 \right\}, \\ \text{"log-lin"} : \lim_{N \rightarrow +\infty} \bar{x}^* &= X, \\ \text{"linear"} : \lim_{N \rightarrow +\infty} \bar{x}^* &= X. \end{aligned}$$

In the first two cases, the red zone decreases as population increases until reaching a risk sanctuary, that is a hard red zone that is preserved as the population increases unrestrictedly. In the last two cases, the red zone increases as population increases (at least ultimately as the log-lin case), and the risk sanctuary occupies all the space for a finite population size, squeezing everybody onto the crest.



Linear-log utility function

Log-log utility function



Log-linear utility function

Linear utility function

Figure 7: Red zone as a function of  $N$  and risk sanctuaries.

The first two cases allow interesting interpretations. In the log-log utility case, if  $\lambda_F$  is small with respect to  $\omega$  for example, then the red zone completely disappears. The needs and means for space overwhelm risk containment. In contrast, if  $\lambda_F$  is large, then the red zone tends to an ultimate risk sanctuary.

## 6 Conclusion

This paper is an examination of the urbanization of areas exposed to natural disasters. We analyze the power and limitations of core determinants: land-use and insurance policies. In principle, they are perfect substitutes, one being the other's dual (non-price vs. price policies).

Current policies are simple: they are based on a very small number of zones with differentiated tariffs or density limitations. One reason is that the insurance and land-use regulations cannot be better than the maps they rely on and these maps are not precise. We claim that there is a risk-map paradox. Risk maps are not socially optimal, because they are public goods, the provision of which is often inefficient. Besides, fine risk discrimination, either for insurance or land-use, is politically infeasible.

The most commonly used policy is the "red zone" policy: a red zone where land-use is prohibited and another zone where a single insurance premium is applied. The use of a location-blind premium implies free-riding: households do not pay for the risk they generate by locating in exposed areas. Simple zoning restrictions partially correct the imperfect internalization of risk by households and increase efficiency. We show that the red zone is a powerful tool. Under location-blind premiums, it can achieve a Pareto optimum if the fixed part of risk is null. Even with the non-negligible fixed part, an example developed in this paper suggests that the optimal red zone with a location-blind premium achieves a second-best optimum, with a small welfare loss compared to the first-best optimum.

Risk maps are criticized not only for their lack of precision but also for their obsolescence. The risk-map paradox explains the former problem, not the latter. Updating is all the more important that climate change and demographic pressure modify the existing equilibrium. The impact of climate change and demographic evolution on the design of optimal red zones can be counterintuitive. We have proposed a thorough description of the competing effects in the general case. As expected, extending the red zone as disaster frequency or seriousness increase contains the final incidence. We have constructed contrasted and realistic cases where the red zone shrinks, where it grows, and where it shrinks and then grows, as the population grows.



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## A Appendix

### A.1 Characterization of the first best

Assume that policyholders pay the actuarial premium  $p(x)$  ( $\lambda_F + \lambda_S s$ ) to get full coverage of a dwelling of size  $s$  located at  $x$ , and denote the location-dependent rent by  $r(x)$ . All functions of  $x$  are assumed to be differentiable. We denote by  $s(x)$  the size chosen by policyholders living at location  $x$ .

First-order conditions yield

$$\frac{\partial U / \partial s}{\partial U / \partial z} = r(x) + p(x)\lambda_S. \quad (28)$$

We apply the envelope theorem to the indirect utility function  $V(x)$  where  $x$  is any optimal location choice:

$$\frac{dV}{dx} = 0 = -\frac{\partial U}{\partial z} \left[ \frac{ds(x)}{dx} \left( r(x) + p(x)\lambda_S \right) + s(x) \left( \frac{dr(x)}{dx} + \frac{dp(x)}{dx} \lambda_S \right) + \frac{dp(x)}{dx} \lambda_F \right] + \frac{\partial U}{\partial s} \frac{ds(x)}{dx}.$$

Thanks to (28) and since  $\partial U / \partial z \neq 0$ , we get the equilibrium property

$$s(x) \left( \frac{dr(x)}{dx} + \frac{dp(x)}{dx} \lambda_S \right) + \frac{dp(x)}{dx} \lambda_F = 0. \quad (29)$$

This is the Muth-Mills condition, with the additional term  $(dp(x)/dx)\lambda_S$  and where the fixed part  $p(x)\lambda_F$  of the insurance premium is assimilated with transport costs. Indeed, when households choose location  $x$  and lot size  $s(x)$ , they consider the fixed part  $p(x)\lambda_F$  and the *total rent*  $r(x) + p(x)\lambda_S$ . Two locations are equally attractive only if the total rent is smaller where the fixed part is higher.

Under actuarially fair insurance, density  $n(\cdot)$  decreases and surface  $s(\cdot)$  increases with respect to risk exposure  $x$ . The underlying economic argument goes as follows. Along the isoutility curve where all optimal choices are located, smaller total rent is necessarily associated with more demand for space: Hicksian demand increases as the price decreases. Thus, if insurance rates increase with respect to risk ( $\lambda_F > 0$  and typically with actuarially fair pricing), households demand more space and are thus more dispersed in riskier areas:  $n(\cdot)$  and  $z(\cdot)$  increase with respect to  $x$ , while  $s(\cdot)$  decreases. At the limit, the riskiest areas can be deserted. Because  $r(\cdot)$  increases, we denote  $x_{\text{Actuarial}}^*$  the lowest location in the set of positions where  $r(x) > 0$ . If the whole space is inhabited, then  $x_{\text{Actuarial}}^* = 0$ . In any case,  $x_{\text{Actuarial}}^*$  is the riskiest inhabited location in equilibrium.

### A.2 Comparative statics on the red zone

In the equations below,  $\theta$  stands either for  $\rho$  or  $N$  to economize typing.

**Analysis of the three effects and proof of Proposition 4.** By derivation of (16) with respect to  $\theta$ , we get

$$\left( \frac{\partial \text{MRR}}{\partial x} \cdot \frac{d\bar{x}^*}{d\theta} + \frac{\partial \text{MRR}}{\partial \theta} \right) = \frac{\partial \text{MRS}_{sz}}{\partial z} \cdot \frac{dz}{d\theta} + \frac{\partial \text{MRS}_{sz}}{\partial s} \cdot \frac{ds}{d\theta}. \quad (30)$$

Because

$$\frac{dz}{d\theta} = \frac{\partial z}{\partial \theta} \Big|_{\bar{x}^*} + \frac{\partial z}{\partial x} \cdot \frac{d\bar{x}^*}{d\theta}, \quad (31)$$

$$\frac{ds}{d\theta} = \frac{\partial s}{\partial \theta} \Big|_{\bar{x}^*} + \frac{\partial s}{\partial x} \cdot \frac{d\bar{x}^*}{d\theta}, \quad (32)$$

we get

$$\begin{aligned} \frac{d\bar{x}^*}{d\theta} \left( \frac{\partial \text{MRR}}{\partial x} - \frac{\partial \text{MRS}_{sz}}{\partial z} \frac{\partial z}{\partial x} - \frac{\partial \text{MRS}_{sz}}{\partial s} \frac{\partial s}{\partial x} \right) &= - \left. \frac{\partial \text{MRR}}{\partial \theta} \right|_{\bar{x}^*} + \frac{\partial \text{MRS}_{sz}}{\partial z} \cdot \left. \frac{\partial z}{\partial \theta} \right|_{\bar{x}^*} \\ &+ \frac{\partial \text{MRS}_{sz}}{\partial s} \cdot \left. \frac{\partial s}{\partial \theta} \right|_{\bar{x}^*}. \end{aligned} \quad (33)$$

Remark that  $\partial z/\partial x > 0$ . As  $\partial s/\partial x = -1/N < 0$  and thanks to the technical assumptions (11) and (2), the factor of  $d\bar{x}^*/d\theta$  in (33) above is negative. Therefore the sign of  $d\bar{x}^*/d\theta$  is the sign of the sum of the three effects RIE, RSE, and LSE

$$\underbrace{\left. \frac{\partial \text{MRR}}{\partial \theta} \right|_{\bar{x}^*}}_{\text{RIE}} \underbrace{- \frac{\partial \text{MRS}_{sz}}{\partial z} \cdot \left. \frac{\partial z}{\partial \theta} \right|_{\bar{x}^*}}_{\text{RSE}} \underbrace{- \frac{\partial \text{MRS}_{sz}}{\partial s} \cdot \left. \frac{\partial s}{\partial \theta} \right|_{\bar{x}^*}}_{\text{LSE}}. \quad (34)$$

The signs of  $\partial \text{MRR}/\partial \theta$ ,  $\partial z/\partial \theta$  and  $\partial s/\partial \theta$  are given below.

$$\left. \frac{\partial \text{MRR}}{\partial \rho} \right|_{\bar{x}^*} = \frac{\text{MRR}}{\rho} \geq 0 \quad ; \quad \left. \frac{\partial \text{MRR}}{\partial N} \right|_{\bar{x}^*} = \frac{\lambda_F}{X - \bar{x}^*} (p(\bar{x}^*) - \bar{p}(\bar{x}^*)) \geq 0 \quad ; \quad (35)$$

$$\left. \frac{\partial z}{\partial \rho} \right|_{\bar{x}^*} = -\frac{\text{CR}(\bar{x}^*)}{N\rho} \leq 0 \quad ; \quad \left. \frac{\partial z}{\partial N} \right|_{\bar{x}^*} = \frac{\lambda_S}{N^2} (X - \bar{x}^*) \bar{p}(\bar{x}^*) \geq 0 \quad ; \quad (36)$$

$$\left. \frac{\partial s}{\partial \rho} \right|_{\bar{x}^*} = 0 \quad ; \quad \left. \frac{\partial s}{\partial N} \right|_{\bar{x}^*} = -\frac{X - \bar{x}^*}{N^2} \leq 0. \quad (37)$$

where  $\bar{p}(x)$  is the mean probability in the building zone.

## WEB ONLY SUPPLEMENTAL MATERIAL

### B Efficiency and existence of an equilibrium under actuarially fair insurance

We assume that on each indifference curve  $U(z, s) = u$ ,  $s$  approaches zero as  $z$  approaches infinity. This is a sufficient condition for the existence of an equilibrium which is similar to Assumption 3.1 in FUJITA (1989). Note that this proof only assumes that  $p(\cdot)$  is strictly decreasing.

**Efficiency.**  $U_A^*$  denotes the utility attained in the equilibrium under actuarially fair insurance. Following FUJITA and THISSE (2002), we prove that this equilibrium is efficient by showing that it minimizes the social cost of achieving  $U_A^*$ .

For any allocation that achieves utility  $U_A^*$ ,  $(n(x), z(x), s(x); x' \leq x \leq X)$  where  $x'$  delimits the inhabited area, the social cost for a household at  $x$  to enjoy utility  $U_A^*$  is the sum of the quantity of money  $Z(s(x), U_A^*)$  such that  $U(Z(s(x), U_A^*), s(x)) = U_A^*$  and of the cost of risk  $p(x)(\lambda_F + \lambda_S s(x))$ . Thus, we want to show that the actuarially-fair-insurance equilibrium allocation is a solution of the following program:

$$\min_{x', n(\cdot), s(\cdot)} \int_{x'}^X [Z(s(x), U_A^*) + p(x)(\lambda_F + \lambda_S s(x))] n(x) dx \quad (38)$$

$$\text{s.t. } \begin{cases} \int_{x'}^X n(x) dx = N, \\ \forall x \in [x'; X], n(x)s(x) = 1. \end{cases} \quad (39)$$

A basic rearrangement gives the equivalent maximization program

$$\max_{x', s(\cdot)} \int_{x'}^X \frac{\omega + R_A - Z(s(x), U_A^*) - p(x)(\lambda_F + \lambda_S s(x))}{s(x)} dx, \quad (40)$$

$$\text{s.t. } \int_{x'}^X \frac{1}{s(x)} dx = N, \quad (41)$$

where  $R_A$  is the redistributed rent in the equilibrium. We first neglect constraint (41). We denote

$$\psi(x, s, U_A^*) = \frac{\omega + R_A - Z(s, U_A^*) - p(x)(\lambda_F + \lambda_S s)}{s}, \quad (42)$$

$$\Psi(x, U_A^*) = \max_s \psi(x, s, U_A^*). \quad (43)$$

Program (40) corresponds to

$$\max_{x', s(\cdot)} \int_{x'}^X \psi(x, s, U_A^*) dx = \max_{x'} \int_{x'}^X \Psi(x, U_A^*) dx. \quad (44)$$

As the maximum operator and  $\psi(\cdot, s, U_A^*)$  increase (as  $p(\cdot)$  decreases), by composition  $\Psi(\cdot, U_A^*)$  increases as well. We denote  $x^*$  as the highest value such that  $\Psi(x^*, U_A^*) = 0$  if it exists in  $[0; X]$  and  $x^* = 0$  otherwise. Once the objective is maximized with respect to  $s$ , one efficient value of  $x'$  is  $x^*$ .

It is straightforward that the actuarially-fair-insurance equilibrium allocation is a solution of this rearranged program: at each  $x \geq x'$ ,  $\Psi(x, U_A^*)$  can be interpreted as the bid rent given the proposition to settle at  $x$  with a lot size  $s$  and to pay the actuarially fair premium  $p(x)(\lambda_F + \lambda_S s)$ ;  $x^*$  can be interpreted as the most exposed inhabited area in the equilibrium.

Finally, we know that the equilibrium allocation satisfies constraint (41). Consequently, the equilibrium is efficient.

**Existence.** The proof, which we omit because of its length, is a straightforward adaptation of the proof in FUJITA (1989) (Proposition 3.8). The key argument is based on the concept of ‘‘compensated equilibrium’’, by which the decentralizability of an optimum, via the *uniform* transfer to all, is established.