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How Economic Growth and Rational Decisions Can Make Disaster Losses Grow Faster Than Wealth

Stéphane Hallegatte

Abstract

Assuming that capital productivity is higher in areas at risk from natural hazards (such as coastal zones or flood plains), this paper shows that rapid development in these areas—and the resulting increase in disaster losses—may be the consequence of a rational and well-informed trade-off between lower disaster losses and higher productivity. With disasters possibly becoming less frequent but increasingly destructive in the future, average disaster losses may grow faster than wealth. Myopic expectations, lack of information, moral hazard, and externalities reinforce the likelihood of this scenario. These results have consequences on how to design risk management and climate change policies.

How economic growth and rational decisions can make disaster losses grow faster than wealth

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1   Introduction

It is widely recognized that economic losses due to natural disasters have been increasing exponentially in the last decades. The main drivers of this trend are the increase in population, and the growth in wealth per capita. With more and richer people, it is not surprising to find an increase in disaster losses. More surprising is the fact that, in spite of growing investments in risk reduction, the growth in losses has been as fast as economic growth (e.g., for floods in Europe, see Barredo, 2009; at the global scale, with much larger uncertainties, see Miller et al., 2008, Neumayer and Barthel, 2010), or even faster than economic growth (e.g., in the U.S. and for hurricanes, see Nordhaus, 2010; Pielke et al., 2008; at the global scale, Bouwer et al., 2007). Anthropogenic climate change does not seem to play a significant role in these evolutions, except possibly in very specific cases, for some hazards in some regions (Schmidt et al., 2009; Neumayer and Barthel, 2010; Bouwer, 2011). In the U.S., the trend in hurricane losses relative to wealth can be almost completely explained by the fact that people take more and more risks, by moving and investing more and more in at-risk areas (Pielke et al., 2008).

Most of the time, the explanations offered for this increasingly risk-taking trend are the following:

- Information and transaction costs: since the information on natural hazards and risk is not always easily available, households and businesses may decide not to spend the time, money and effort to collect them, and disregard this information in their decision-making process (Magat et al., 1987; Camerer and Kunreuther, 1989; and Hogarth and Kunreuther, 1995).

- Externalities, moral hazards, and market failures: since insurance and post-disaster support are often available in developed countries, households and firms in risky areas do not pay the full cost of the risk, and may take more risk than what is socially optimal (e.g., Kaplow, 1991; Burby et al., 1991; Laffont, 1995). Also, Lall and Deichmann (2010) show that risk mitigation has positive externalities and that

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private and social costs of disaster losses may differ, leading to inappropriate risk reducing investments.

- Irrational behaviors and biased risk perceptions: Individuals do not always react rationally when confronted to small probability risks, and they defer choosing between ambiguous choices (Tversky and Shafir 1992; Trope and Lieberman, 2003). Moreover, they have trouble to take into account events that have never occurred before (the "bias of imaginability", see Tversky and Kahneman, 1974). Finally, private and public investment decisions do not always adequately take long and very long-term consequences into account (for public decisions, see Michel-Kerjan, 2008; for private decisions, see Kunreuther et al. 1978, and Thaler, 1999).

There is no doubt these factors play a key role. But this move toward at-risk areas could also be a rational decision — motivated by higher productivity in at-risk areas — rather than a market failure. Kellenberg and Mobarak (2008) suggested that rational decisions could explain non-monotonic trends in disaster deaths. This paper shows that they may also lead to increasing economic losses.

Many investments have higher productivity in at-risk areas than in risk-free zones, and bring benefits that justify increased levels of risk.[2] As suggested by Bouwer (2011), this is particularly true for areas at risk from floods and coastal storms. For instance, international harbors and tourism create jobs and activities that attract workers in coastal zones in spite of flood risks. When economic growth is driven by export, the attractiveness of coastal zones is reinforced because these regions allow for easier and cheaper exports. In China, for instance, Fleisher et Chen (1997) find that Total Factor Productivity (TFP) is 85 percent higher in coastal regions than in inland region, and that TFP growth rates are not significantly different in spite of higher investment in inland regions, suggesting a permanent productivity advantage in coastal regions. Also, cheap waterway transport attracts industrial production close to flood plains, and partly explains why most large cities are located on rivers.

From the activities that benefit from being located in a risk-prone area, such as coastal zones, additional investments are then carried out to benefit from agglomeration externalities on productivity and reduced transportation costs (Ciccone et al., 1996; Ciccone, 2002; World Bank, 2008; Lall and Deichmann, 2010). Gallup et al. (1998) analyze the impact of geography and transportation costs on productivity and growth, and find that areas with lower transportation costs are more productive; these areas are also often more at risk from floods, because they are on the coast or next to rivers. As an illustration, landlocked countries have higher transportation costs (measured by the shipping costs),

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[2]Productivity is considered here in a broad sense. For instance, the amenities provided by the proximity to water (e.g., near the Floridian beaches) can be considered as a higher productivity from housing services and leisure activity.

and had over the 1965-1990 period a growth rate on average 1 percent lower than coastal countries, which are at risk from coastal floods and storms.

Also, the drivers of economic growth are concentrated in cities, and productivity and productivity growth is larger in cities (World Bank, 2008). Reviewing evidence from eight developing countries, Fields (1975) reports per capita income in urban areas from two to eight times larger than in rural areas. Lu (2002) shows that in China from 1990 to 1999, the urban-rural per capita consumption ratio lies between 1.5 and 5. At the global scale, World Bank (2008) reports urban-rural income ratios between 1.5 for developed countries and up to 3 for developing countries, suggesting much higher productivity in cities at all stages of development. Differences are also large for consumption, with urban consumption premiums (compared with rural consumption) that are always positive and frequently exceed 50 percent. Not only is productivity and consumption higher in urban areas, but amenities are also often superior: among low-income countries with urban population shares of less than 25 percent, access to water and sanitation in towns and cities is around 25 percentage points higher than in rural areas (World Bank, 2008). These differences create strong incentives for rapid rural-urban migration. Confronted with land scarcity and high land costs in large cities, this migration has led to construction in at-risk areas (e.g., Burby et al., 2001; Burby et al., 2006; Lall and Deichmann, 2010). In the most marginal and risky locations, informal settlements and slums are often present, putting a poor and vulnerable population in a situation of extreme risk (e.g., Ranger et al., 2011).

One can make the case, therefore, that population and asset migrations to at-risk areas, and the resulting increase in disaster losses, are not solely due to lack of information, irrational behaviors and moral hazard, as often suggested, but also to a rational trade-off between lower disaster losses and higher productivity in risky areas (as suggested in their analysis of disaster deaths by Kellenberg and Mobarak, 2008).

Compared with previous investigations of trends in disaster economic losses (e.g., Lewis and Nickerson, 1989; Schumacher and Strobl, 2008), this analysis stresses the existence of benefits from investing in at-risk areas, investigates both investments in at-risk locations and risk mitigation choices in a common framework, and highlights the trade-off between lower disaster losses and higher productivity.

Within this framework and under some conditions, it is found that — even with no change in climate conditions and hazard characteristics — natural disasters may become more destructive in the future and that average losses may increase faster than wealth and income. This increase would arise from an intuitive mechanism: economic growth leads to better protections against natural disasters, which in turns make it rational to invest more in at-risk areas, worsening the consequences when disasters occur in spite of protections. If the worsening of disaster consequences dominates the decrease in disaster probability, average losses can increase, and they can do so faster than income and wealth growth.

This possibility has important consequences on how to design risk management and risk reduction policies and how to deal with climate change. These aspects are discussed in the conclusion, which can be read independently of the more technical first sections of this paper.

2 Larger disasters in a wealthier world?

It is generally accepted that richer populations invest more to protect themselves from natural hazards. A richer population, however, may also invest more in at-risk areas, increasing exposure to natural hazards. These two trends have opposite impacts on risk, and the resulting trend in risk is thus ambiguous. This trend is investigated in this section with a simple model.

2.1 A balanced growth pathway

Let us assume a balanced economy, in which economic production is done using productive capital only, with decreasing returns:

$$Y_b = f(K_b) = \psi K_b^\phi \tag{1}$$

The variable Y_b is annual production (i.e. value added) in the balanced growth pathway; K_b is the corresponding amount of productive capital; and ψ is total productivity. All variables are time dependent, and are assumed to grow over time. Productivity is growing at a rate λ.

$$\psi(t) = \psi(0)e^{\lambda t} \tag{2}$$

Assuming the economy is on a balanced growth pathway, production and capital are also growing at the same rate:

$$Y_b(t) = Y_b(0)e^{\mu t} \tag{3}$$
$$K_b(t) = K_b(0)e^{\mu t} \tag{4}$$

To be consistent, Eq.(1 to 4) require:

$$Y_b(0)e^{\mu t} = \psi(0)e^{\lambda t}\left(K_b(0)e^{\mu t}\right)^\phi \tag{5}$$

which means:

$$\mu = \frac{\lambda}{1 - \phi} \tag{6}$$

and

$$Y_b(0) = \psi(0)K_b(0)^\phi \tag{7}$$

2.2   The trade-off between higher productivity and lower disaster losses

Let us now assume that the amount of capital K_b can be either located in safe locations (K_s) or in risky locations (K_r), with $K_b = K_s + K_r$. Examples of risky locations are coastal areas, where storm surge and coastal floods are possible, as well as areas at risk of river floods, high-concentration urban areas at risk of floods in case of heavy precipitations, and hurricane-prone regions. We assume that risky locations are more productive, thanks to their location (e.g., proximity from port infrastructure for export-oriented industries; coastline amenities for tourism; easier access to jobs in at-risk locations in crowded cities). This increase in production has decreasing returns, however. As a consequence, total production becomes:

$$Y = Y_b + \Delta Y = Y_b + \alpha K_r^\gamma \tag{8}$$

where ΔY is the additional output produced thanks to the localization of capital in risk-prone areas; α is a relative productivity advantage, and is assumed to grow at the same rate than general productivity ψ (i.e., at the rate λ).

The capital located in the risky area can be affected by *hazards*, like floods and windstorms. If a hazard is too strong, it causes damages to the capital installed in at-risk areas, and can be labeled as a *disaster*. To simplify the analysis, we assume that in that case, the capital at-risk is totally destroyed. It is assumed that this is the only consequence of disasters. Disaster fatalities and casualties are not considered in this simple model, assuming that early warning, evacuation, emergency services, and higher quality housing and infrastructure can avoid them, which is consistent with the observation that disaster deaths decrease with income, at least above a certain income level (Kahn, 2005; Kellenberg and Mobarak, 2008).[3] Moreover, additional indirect economic consequences (Hallegatte and Przyluski, 2011, Strobl, 2011) are not taken into account.

These disasters (i.e. hazards that lead to capital destruction) have a probability p_0 to occur every year, except if protection investments are carried out and reduce this probability. These protection investments take many forms, depending on which hazard is considered. Flood protections include dikes and seawalls, but also drainage systems to cope with heavy precipitations in urban areas. Windstorm and earthquake protections consist mainly in building retrofits and stricter building norms, to ensure old and new buildings can resist stronger winds or larger earthquakes.

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[3]Human losses could be taken into account if it is assumed that fatalities and casualties can be measured by an equivalent economic loss, which is highly controversial; see a discussion in Viscusi and Aldy (2003).

It is assumed that better defenses reduce the probability of disasters, but do not reduce their consequences. This is consistent with many types of defenses, like seawalls that can protect an area up to a design standard of protection but fail totally if this standard is exceeded.[4] Better defenses are also more expensive, and the annual cost of defenses C and the remaining disaster probability p are assumed linked by the relationship:[5]

$$C(p) = \xi \left(\frac{1}{p^\nu} - \frac{1}{p_0^\nu} \right) \tag{9}$$

so that the cost of reducing the disaster probability to zero is infinite. Depending on the value of ν, protection costs increase more or less rapidly when the disaster probability approaches zero. The parameter ν therefore corresponds to more or less optimistic assumptions on protection costs.

Any given year, the economic output is given by:

$$Y = Y_b + \alpha K_r^\gamma - C(p) - L \tag{10}$$

where L is the damages from disasters, and is given by a random draw with probability p. If a disaster occurs, losses are equal to K_r, i.e. all the capital located in the risky area is destroyed. Any given year, the expected loss $E(L)$ is equal to pK_r and the expected output is equal to:

$$E(Y) = Y_b + \alpha K_r^\gamma - C(p) - pK_r \tag{11}$$

2.3   Optimal choice of p and K_r

Assuming a social planner — or an equivalent decentralized decision-making process — decides the amount of capital K_r to be located in the risky area and the level of protection that is to be built, its program is:[6]

$$\begin{aligned} \max_{p,K_r} \ & E(Y) \\ s.t. K_r \leq K_b \ & \text{and } 0 \leq p \leq p_0 \end{aligned} \tag{12}$$

We neglect risk aversion and we assume that the expected production is maximized, not the expected utility. Doing so is acceptable if disaster losses remain small compared

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[4]Also, the analysis with rational decision-makers is carried out assuming that there is no risk aversion. In that case, reducing the probability of a disaster or the consequences in case of disaster is equivalent, making this assumption irrelevant.

[5]The probability p here includes both the probability that an event exceeds protection capacities, and the defense failure probability, even for weaker events.

[6]This model is different from the model of Schumacher and Strobl (2008). In the latter, the only decision concerns protection investments that mitigate disaster consequences, and there is no benefit from taking risks and thus no trade-off between safety and higher income.

with income, consistently with the Arrow-Lind theorem for public investment decisions
(Arrow and Lind, 1970). However, this condition holds only if disaster losses can be
pooled among a large enough population (e.g., a large country), and with many other
uncorrelated risks, i.e. in the presence of comprehensive insurance coverage or post-
disaster government support. In small countries (where a disaster can strike a large share
of the population), or where insurance, reinsurance, and post-disaster support are not
available, individual disaster losses can represent a large share of individual income and
savings, and the objective function needs to include risk aversion.

First order conditions lead to the optimal values of p and K_r:

$$\overline{p} \;=\; (\nu\xi)^{\frac{\gamma-1}{\gamma+\nu(\gamma-1)}}(\alpha\gamma)^{\frac{1}{\gamma+\nu(\gamma-1)}} \tag{13}$$

$$\overline{K_r} \;=\; (\nu\xi)^{\frac{1}{\gamma+\nu(\gamma-1)}}(\alpha\gamma)^{-\frac{\nu+1}{\gamma+\nu(\gamma-1)}} \tag{14}$$

Assuming for now that $\overline{K_r} \leq K_b$ and that $\overline{p} \leq p_0$, the expected annual loss at the
optimum is equal to:

$$\overline{E(L)} \;=\; (\nu\xi)^{\frac{\gamma}{\gamma+\nu(\gamma-1)}}(\alpha\gamma)^{-\frac{\nu}{\gamma+\nu(\gamma-1)}} \tag{15}$$

At the optimum, the loss in case of disaster is equal to:

$$\overline{L} \;=\; (\nu\xi)^{\frac{1}{\gamma+\nu(\gamma-1)}}(\alpha\gamma)^{-\frac{\nu+1}{\gamma+\nu(\gamma-1)}} \tag{16}$$

When productivity α is growing over time at the rate λ, there are two possibilities,
depending on the value of γ, the exponent representing decreasing returns in the additional
productivity from capital located in at-risk areas (see Eq. (8)).

Proposition 2.1 *If $\gamma > \nu/(\nu+1)$, then $\overline{K_r}$ and $\overline{E(L)}$ are decreasing over time in absolute
terms. In that case, less and less capital is installed in the risky area when productivity
and wealth increase. So, the absolute level of risk is decreasing with wealth. It is also
noteworthy that, in such a situation, annual mean losses and capital at risk counter-
intuitively decrease if protection costs (ξ) increase. If $\gamma < \nu/(\nu+1)$, then the amount of
capital at-risk increases, and the risk (both in terms of average loss and maximum loss)
is increasing with wealth, and mean annual losses and capital at risk are augmented if
protection costs (ξ) increase.*

But the absolute level of risk is not a good measure of risk: a wealthier society is able
to cope with larger losses. The question is therefore the relative change in risk. One way
of investigating this question is to assess whether $\overline{K_r}$ and $\overline{E(L)}$ are growing more or less
rapidly than Y_b and K_b, i.e. at a rate larger or lower than μ.

If α is growing at a rate λ, expected losses $\overline{E(L)}$ are growing at a rate $\lambda \frac{-\nu}{\gamma + \nu(\gamma - 1)}$ and maximum losses (i.e., the losses in case a disaster occurs), $\overline{K_r}$, are growing at a rate $\lambda \frac{-(\nu+1)}{\gamma + \nu(\gamma - 1)}$. Since K and Y are growing at a rate $\mu = \lambda/(1 - \phi)$, we have the following result:

Proposition 2.2 *If $\phi \frac{\nu}{\nu+1} < \gamma < \frac{\nu}{\nu+1}$, then mean annual losses $\overline{E(L)}$ are growing faster than baseline economic output Y_b. If $\phi - \frac{1}{\nu+1} < \gamma < \frac{\nu}{\nu+1}$, then the capital at risk and the losses in case of disasters (i.e. $\overline{K_r}$) are growing faster than Y_b.*

With usual values for ϕ, i.e. about 1/3, and the simplest assumption for protection cost, i.e. $\nu = 1$, losses in case of disasters are growing faster than Y for any γ, positive and lower than 1/2. Mean annual losses increase faster than Y_b if γ is between 1/6 and 1/2. Therefore, it is possible that disaster maximum losses and mean annual losses increase with wealth in the future, *even in relative terms*.

In this case, all capital will eventually be installed in at-risk areas ($\overline{K_r} = K_b$), and a disaster would lead to the complete destruction of all production capacities, with a probability $\overline{p} = \left(\frac{\xi \nu}{K_b} \right)^{\frac{1}{1+\nu}}$.

Figure 1 summarizes these findings, for $\phi = 1/3$. It shows four zones, as a function of the values of the parameters ν and γ. In a significant portion of the parameter space, labeled "zone 2", the capital at-risk and the mean annual losses increase, even in relative terms when compared with total economic output. In this zone, therefore, disasters become less and less frequent, but they are more and more destructive, in such a way that the risk — i.e., the average losses — increases more rapidly than wealth and income.

Surprisingly, the increase in risk happens when γ is small enough, i.e. when additional productivity from locating capital in at-risk areas exhibits sufficiently diminishing returns. Consistent with intuition, however, is the fact that increase in risk is more likely when ν is large, i.e. when protection costs are increasing rapidly with the protection level. It is interesting to note that absolute protection costs (ξ) and the absolute additional productivity (α) do not influence the behavior of mean annual losses and capital at risk, but only their levels.

If $\gamma = \nu/(\nu + 1)$, there is no inside maximum in Eq. (12). Instead, there are two possibilities depending on the protection cost relative to the additional productivity in at-risk areas. If the additional productivity is high enough (relative to protection costs), then all capital is located in at-risk area ($\overline{K_r} = K_b$). If the additional production is not sufficient, then no protection is provided ($\overline{p} = p_0$).

The limit between these two possibilities depends on the protection costs, relative to the additional productivity in at-risk areas. The limit protection cost (ξ_l) can be written as a function of the additional productivity α as:
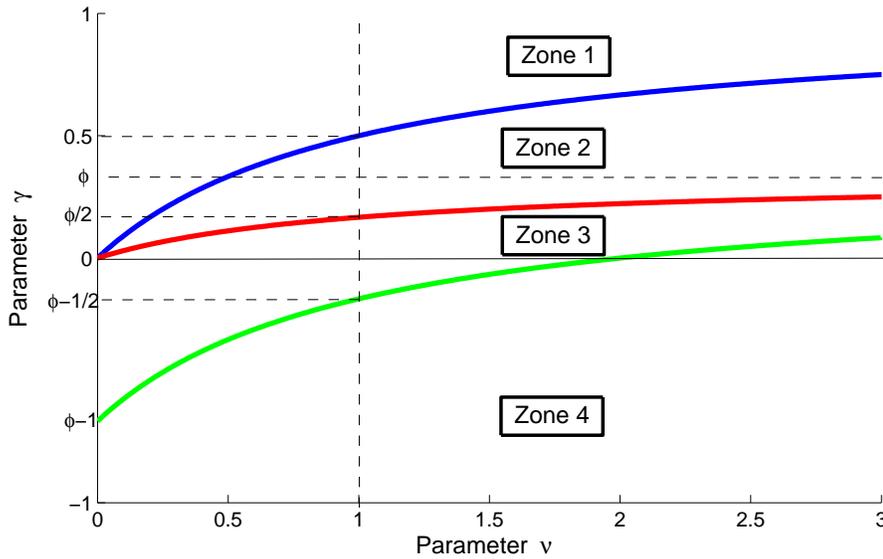
Figure 1: Behaviors of the optimal mean annual losses ($\overline{E(L)}$) and of the optimal capital in at-risk areas (or, equivalently, of the losses in case of disaster) ($\overline{K_r}$), as a function of the values of the parameters γ and ν. There are four zones delimited by continuous lines. In the first zone, on the top of the figure, mean annual losses and capital at risk decrease in absolute terms when the productivity increases. In the second one, the capital at risk and the mean annual losses increase with productivity, both in absolute and relative terms (with respect to to total output and productive capital). In the third zone, the capital at risk still increases in absolute and relative terms, but the mean annual losses increase only in absolute terms (they decrease in relative terms). In the fourth zone, at the bottom of the figure, mean annual losses and capital at-risk increase in absolute terms but both decrease in relative terms.

$$\xi_l(\alpha) = \left(\frac{\alpha}{1 + \nu}\right)^{(1+\nu)} \nu^{\nu} \tag{17}$$

and — equivalently — the limit additional productivity can be written as a function of protection costs:

$$\alpha_l(\xi) = (1 + \nu)c^{-\frac{\nu}{1+\nu}}\xi^{\frac{1}{1+\nu}} \tag{18}$$

Proposition 2.3 *If $\gamma = \nu/(\nu + 1)$ and $\xi > \xi_l(\alpha)$ (or, equivalently, $\alpha < \alpha_l(\xi)$), then no protection is provided ($\overline{p} = p_0$) and the capital in at-risk areas is equal to $\overline{K_r} = \left(\frac{\alpha\nu}{p_0(1+\nu)}\right)^{(1+\nu)}$. If $\gamma = \nu/(\nu + 1)$ and $\xi < \xi_l(\alpha)$ (or, equivalently, $\alpha > \alpha_l(\xi)$), then all capital is located in at-risk areas ($\overline{K_r} = K_b$), and the protection is such that the disaster probability is equal to $\overline{p} = \left(\frac{\xi\nu}{K_b}\right)^{\frac{1}{1+\nu}}$.*

2.4 Preliminary conclusion

In a reasonable framework and in a large parameter domain, a simple optimization suggests that improved protection against frequent hazards can lead to increased exposure to and losses from exceptional hazards. The consequence is that, as observed by ISDR (2009), poor countries suffer mainly from frequent and low-cost events, while rich countries suffer from rare but catastrophic events. Our analysis also suggests that the overall risk — i.e. mean annual losses — can increase with time, and that it can increase faster than wealth, even if all decisions are based on rational trade-offs between income and safety.

The model shows that the observed increase in disaster losses may not be due to irrational behaviors and could be the result of rational decisions. If these assumptions are correct, an increasingly wealthy world could see less disasters, but with increasingly large consequences, resulting in average annual losses that keep increasing more rapidly than income. Accounting for indirect disaster impact (see, e.g., Hallegatte and Przyluski, 2011, Strobl, 2011) or for changes in risk aversion with wealth may alter this conclusion by augmenting disaster impacts in Eq. (11) or changing the objective function in Eq. (12).

3 Taking into account myopic behaviors and imperfect information

This result assumes that both protection (i.e., p) and capital investment (i.e., K_r) decisions are made rationally and with perfect knowledge of natural risks. This last assumption appears unrealistic, since many decisions are made using risk analysis based only on recent

past experience, when risk is not simply disregarded (Magat et al., 1987; Camerer and Kunreuther, 1989; and Hogarth and Kunreuther, 1995). This section proposes a modified model to take into account this under-optimality in decision-making.

In this modified model, we assume that capital investment decisions are made with imperfect knowledge, using risk assessments based on events of the recent past. This assumption is consistent with the observation that most capital investment decisions are not made using all available disaster risk information, and that risk-based regulations (e.g., zoning policies) have had a limited impact on new developments in at-risk areas (on the U.S. National Flood Insurance Program regulations, see for instance Burby, 2001).

On the other hand, we model protection decisions as made with perfect knowledge of natural risks and assuming (wrongly) that capital investment decisions will then also be made optimally and with perfect knowledge. There is thus an inconsistency in the model between protection decisions and capital investment decisions. This hypothesis is justified by the fact that (public and private) protection decisions are most of time designed through sophisticated risk analyses, taking into account all available information and assuming optimal behaviors.

To assess the consequence of this myopic behavior, it is necessary to go beyond analytical calculations, and use a numerical model. This model is extremely simple, and based on the calculations from the previous section. The model has a yearly time step. Each year, the baseline output Y_b increases at the rate μ, and the additional productivity α from at-risk capital increases at the rate λ. To decide on the optimal protection level, perfect knowledge is assumed, leading to the same protection levels as in the previous section:

$$\overline{p} = \xi^{\frac{\gamma-1}{2\gamma-1}}(\alpha\gamma)^{\frac{1}{2\gamma-1}} \tag{19}$$

Then, a decision is made on the amount of capital to install in at-risk areas. We assume that this decision is made independently each year, with no inertia. It means that the optimization can be done in a static manner, with no intertemporal optimization.

We assume decisions on the amount of capital to install in the risky area are based on a disaster probability that is estimated empirically, not on the exact probability. To do so, the model includes a random process, which decides — each year — whether a disaster occurs. In practice, $F(t) = 1$ if there is a disaster during the year t, and $F(t) = 0$ otherwise. The real disaster probability is $\overline{p}$. The empirically estimated disaster probability is $\hat{p}(t)$ and is given by:

$$\hat{p}(t) = \sum_{j=-\infty}^{j=t} e^{-\frac{t-j}{\tau}} F(j) \tag{20}$$

This modeling corresponds to backward-looking myopic expectation, in which past events have an exponentially decreasing weight (with time scale τ). In other terms, agents assess future disaster risks from past events, with a memory characteristic time τ. The consequence is that the estimated disaster probability is higher than the real one just after a disaster, and lower than the real one when no disaster has occurred for a while. This behavior appears consistent with many observations (e.g., Kunreuther and Slovic, 1978; Tol, 1998).

Investment decisions are based on this empirical probability, and the amount of capital in at-risk area is:

$$\hat{K}_r = \left(\frac{\hat{p}}{\alpha\gamma}\right)^{\frac{1}{\gamma-1}} \tag{21}$$

Just after a disaster, $\hat{p}(t)$ is larger than $\overline{p}(t)$, disaster risks are overestimated, the capital in the risky area is lower than its optimal value, and output is lower than its optimal value. After a period without disaster, $\hat{p}(t)$ is lower than $\overline{p}(t)$, disaster risks are underestimated, the capital in the risky area is higher than its optimal value. As a consequence, output is higher than its optimal value in absence of disaster, but losses are larger if a disaster occurs. On the average, output is also lower than its optimal value, since additional production thanks to higher productivity in risky areas does not compensate for larger disaster losses.

The efficiency of this empirical process depends on the disaster probability. If there are many disasters over a period τ (i.e. if $1/\overline{p} << \tau$), the estimated probability remains close to the real one. If the memory is too short, i.e. if τ is too low, then the estimated probability will often be different from the real one.

This numerical model is created and simulated with ad hoc parameter values, as an illustration of its results. Parameters are provided in Tab. 1; results are robust for different choices for these parameters, except for γ, as shown in Section 2.3. In this numerical exercise, we choose $\nu = 1$ and select a value for γ such that mean annual losses increase with wealth in relative terms, i.e. $\phi\frac{\nu}{\nu+1} < \gamma < \frac{\nu}{\nu+1}$ (the second zone in Fig. 1).

Results from one simulation are provided in Fig. 2 and Fig. 3. Figure 2 shows the real disaster probability $\overline{p}$, which is decided through a perfect-information cost-benefit analysis (see Eq.(19)), and the estimated disaster probability $\hat{p}$, which is assessed through a myopic estimation (see Eq.(20)). After each disaster, the estimated disaster probability is higher than the real one; when no disaster occurs for a long enough period of time, the estimated disaster probability is below the real value.

Figure 3 shows in the upper panel the additional output thanks to the presence of capital in the risky area (i.e. $\alpha K_r^\gamma - C(p) - L$, see Eq.(10)), with perfect information or myopic behavior.[7] It shows a production that depends on the amount of capital at risk:

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[7]In this figure, the recovery and reconstruction are instantaneous, like in a world with infinite recon-

Name	Description	Value
$Y(0)$	Initial production	10.
phi	Capital decreasing return parameter	1/3
λ	Growth in general productivity	2%
α_0	Initial value of the additional productivity from capital in at-risk areas	0.4
γ	Parameter describing the decreasing returns of investments in at-risk areas	0.2
p_0	Disaster probability in absence of protections	0.8
ξ	Parameter for absolute protection costs	0.035
ν	Exponent in protection costs	1
τ	Probability estimation memory timescale	5 years

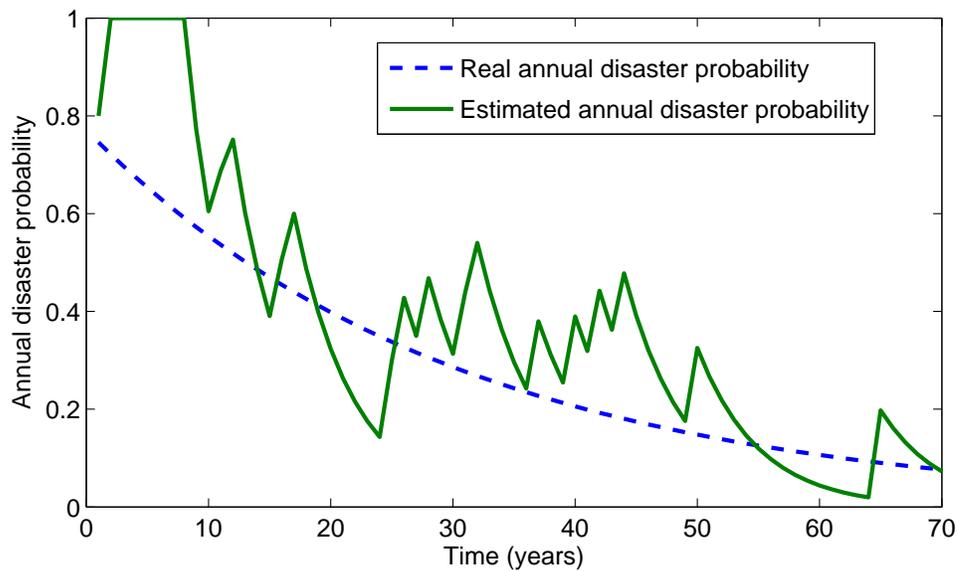Table 1: Parameters of the model.

Figure 2: Real disaster probability $\overline{p}$, decided through a perfect-information cost-benefit analysis (see Eq.(19)), and estimated disaster probability $\hat{p}$, assessed through a myopic adaptive reactive anticipation process, for one random realization.

the larger the amount of capital, the larger the additional production. But when a disaster occurs, this capital located in the risky area is wiped out, and this loss is recorded as an output loss, i.e. through a drop in output. With myopic behavior, the amount of capital at risk is too low when disaster probability is overestimated, and too high when this risk is underestimated. When the risk is underestimated, additional output is larger than its optimal value when no disaster occurs, but the drop in case of disaster is augmented, such that the average output is lower. The bottom panel of Fig. 3 shows the total output, i.e. Y, with perfect information and myopic behavior. As a baseline, the output when no capital is located in the risky area is also represented. The total output is higher than the baseline output thanks to the location of capital at risk. When a disaster strikes, however, total output is lower than the baseline.

In the myopic behavior case, at the end of the period, the productivity is high, and the standard of protection is thus high. In other terms, the disaster probability is very low thanks to good protection. In such a situation, disasters are rare and the estimated disaster probability gets rapidly lower than the real one, prompting an over-investment in the at-risk area. The consequence is a larger disaster with myopic behavior than with perfect information.

So, adding myopic behaviors amplifies our previous results. With perfect information, the population is more protected when it gets richer, the disaster probability decreases over time. But disasters become larger and larger when they occur. With myopic behavior, the interval between two disasters rapidly becomes larger than the memory of the probability estimation process, and there is over-investment in at-risk areas, making disasters more catastrophic. There is thus a potential negative side-effect from higher protection, in the form of an increased vulnerability to exceptional events that exceed the protection capacity.

This trend toward larger disasters is even likely to be enhanced by other processes influencing vulnerability, and especially indirect disaster impacts. In their industrial organization, businesses make trade-offs between their efficiency in normal conditions and their resilience in case of unexpected shock (e.g., Henriet et al., 2012). For instance, there is a tendency to reduce inventories and the number of suppliers to increase efficiency and reduce costs. This strategy increases efficiency and reduces costs when all suppliers are able to produce on demand. But in case of an exogenous shock, a disaster or the bankruptcy of a supplier, reduced inventories and reliance on few suppliers can easily turn into operational problems, as illustrated by the economic perturbations caused by the Icelandic volcano eruption in 2010 or the recent Tohoku-Pacific earthquake in Japan. In the same way, networks-shaped infrastructure (e.g., transportation or electricity infrastructure) can be designed with redundancy to increase robustness in case of disasters, but this

struction capacity. In reality, there are strong constraints on reconstruction, and it can take several years to return to the pre-disaster situation; see, e.g., Hallegatte (2008).
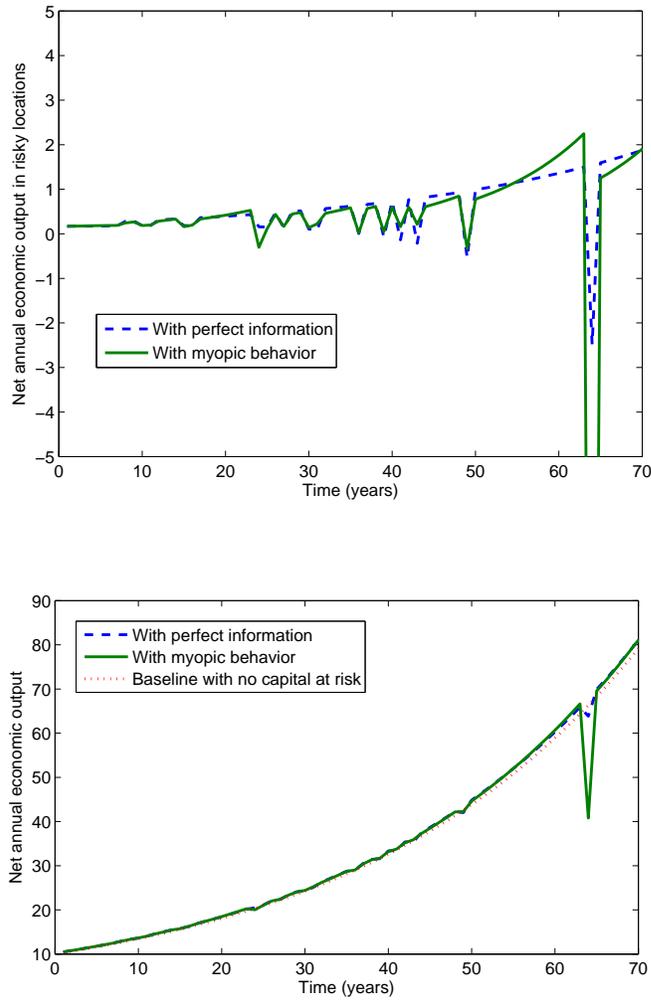
Figure 3: In the upper panel, additional output thanks to the presence of capital in the risky area (i.e. $\Delta Y = \alpha K_r^\gamma - C(p) - L$, see Eq.(10)), with perfect information or myopic behavior. In the bottom panel, total output, i.e. Y^*, with perfect information and myopic behavior, and the baseline output when no capital is in at-risk locations.

option make them more expensive in absence of disaster. In a situation in which disasters are more and more exceptional, it is likely that businesses and other decision-makers will focus even more on efficiency and less on disaster resilience. Such a trend would increase the overall economic vulnerability, and would enlarge the welfare and economic consequences of any disaster.

4   Policy implications

This paper proposes an economic framework to analyze the trade-off between disaster losses and higher capital productivity in areas at risk from natural hazards. It suggests that natural disasters become less frequent but more costly when productivity and wealth increase. Current trends in disaster losses appear consistent with this prediction (e.g., Etkin, 1999; Nordhaus, 2010; Bouwer et al., 2007; Pielke et al., 2008; Bouwer, 2011). These results are also in line with ISDR (2009), which observes that poor countries suffer from frequent and low-cost events, while rich countries suffer from rare but high-cost events. This trend is illustrated by the case of Japan. Thanks to strict building norms, the country can cope with no damages with frequent earthquakes that would cause disasters in any other place of the world. But this resilience allows for higher investments in at-risk areas, and exceptional quakes like the recent Tohoku Pacific earthquake can then lead to immense losses. There is thus a potential negative side-effect from higher protection against disaster, in the form of an increasing vulnerability to exceptional events.

In some cases, this negative side-effect leads to an increase in risk level, in spite of continuously improving protection. Indeed, the model suggests that the overall risk — i.e. mean annual losses — can increase with time in spite of a decreasing disaster probability. The risk can even increase faster than wealth in some circumstances. A consequence of these findings is that future increase in disaster losses might be difficult to avoid. Increasing losses may even be desirable from an economic point-of-view, provided that (i) human losses can be avoided (thanks to warning and evacuation); (ii) affected populations are supported in disaster aftermaths or have access to insurance, to make sure individual losses remain small and the conditions of the Arrow-Lind theorem are respected (i.e., risk aversion can be neglected). This paper suggests a strong and increasing need for post-disaster support, through insurance, ad hoc support, emergency and crisis-management arrangements, in addition to investments in disaster protections, hazard forecasts, and early warning.

Not all risks are linked to rational choices, however. We showed that imperfect information and myopic expectations can amplify risk-taking behaviors. This effect can be reinforced by other sub-optimalities. In particular, some economic agents have little flexibility in their localization choices, like the poorest households who locate in informal settlements in developing-country cities. Also, risk involves externalities: when many

buildings are destroyed by an earthquake, the economic system is paralyzed and collective losses exceed the sum of initial private losses (Lall and Deichmann, 2010; Henriet et al., 2011). These risk amplification mechanisms and externalities may lead economic agents to accept more risk than what is socially optimal. These important sub-optimalities provide ample justification for public action to manage risks and limit risk-taking behaviors. But our results suggest that this action should not systematically aim at *reducing the level of risk*. Instead, it should aim at *managing the level of risk*, to limit disaster losses while making sure that we can still take the worthwhile risks that yield large benefits. In other terms, disaster risk management policies should be favored over disaster risk reduction policies.

Disaster risk management policies need to acknowledge the benefits from investing in at-risk areas, and take these benefits into account in their design. If individuals and businesses take risks that are inappropriate at the social scale, the best course of action is different depending on what explains this behavior. If it is due to irrational behaviors and imperfect information only, then communication tools and land-use regulations are easy to implement and should be able to reduce the level of risk. But if this behavior is also justified by the benefits derived from investing and settling in at-risk areas, then efficient risk management policies will fail or be economically detrimental if they do not provide alternatives to get similar benefits without taking those risks. If investment in risky coastal areas are explained by the benefits from the proximity of a port, for instance, then risk can be reduced by providing businesses with safe development areas that are connected to the port by efficient transport infrastructure. And when activities require proximity to the port and no alternative exists, then investment should be allowed in at-risk areas, provided that a) social benefits justify it, and b) specific risk mitigation actions are undertaken (from warning and evacuation systems to compulsory insurance with risk-based premium). Similarly, if newcomers settle in risky areas of mega-cities because it is the only way to have access to the jobs and opportunities offered by the city, then risk cannot be reduced by simply prohibiting settlements in these areas. Such a policy would face strong political opposition and, if implemented, might lead to the creation of informal settlements, thereby increasing the level of risk instead of reducing it. An efficient policy should rather propose viable alternatives to newcomers, for instance by providing cheap and rapid (possibly subsidized) public transportation from job centers to safe areas that can be developed.

The typical approach for risk mitigation is based on "flood zoning," i.e. on the definition of flood-prone areas where investment and settlement are prohibited. This approach, however, faces difficulties in implementation and enforcement, because it neither distinguishes among different types of economic activities nor accounts for potential benefits from at-risk investments. A more flexible approach that accounts for these benefits — through economic analysis or consultative processes — is more likely to be effective in

reducing risks and to provide net economic benefits. More generally, disaster risk management policies need to shift from a purely negative stance — indicating where it is prohibited to invest and settle — to a more positive approach — indicating where investments should be directed, and providing complementary measures that can make these investments as beneficial as those is at-risk areas. To do so, risk management should not focus only on at-risk areas, but follow a more holistic approach, integrated in development planning. Sometimes, building a transportation infrastructure to connect job centers to safe housing areas is more efficient to reduce risk levels than building dikes to protect a flood-prone zone.

These results also have consequences on climate change policies. First, they show that economic growth has no theoretical reason to automatically reduce disaster losses, even in relative terms. And if empirical results suggest that growth and development lower the number of deaths from disasters (Kahn, 2005), at least above a certain level of income, the evidence concerning their impact on disaster economic losses is mixed and inconclusive. It implies that reducing disaster economic losses requires a specific, targeted policy action.

Moreover, it is likely that socio-economic drivers will remain the dominant drivers of future changes in disaster losses. Some have derived from this result the idea that policy-makers should focus on reducing trends in disaster exposure and vulnerability, not on mitigating climate change (e.g., Pielke et al., 2005). But if socio-economic drivers of losses are the consequence of a desirable trade-off and yield significant benefits, as suggested here, it might not be rational to oppose them in a systematic way. Anthropogenic climate change may increase disaster losses without providing any benefits in return. When comparing two drivers of disaster losses, the question should not be to identify which one is responsible for the larger increase in losses, but which one is the most cost-effective lever to reduce losses. The possibility of increasing disaster losses not driven by settlement in risky areas for economic benefit but by anthropogenic climate change are therefore likely to represent a powerful incentive to mitigate greenhouse gas emissions.

5   Acknowledgments

6   References

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