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Coordinating Flood Insurance and Collective Prevention Policies : A Fiscal Federalism Perspective

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Coordinating Flood Insurance and Collective Prevention Policies: A Fiscal Federalism Perspective *

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Abstract

The protection level that defines risk exposure and household financial coverage are key economic issues for flood management. They interact with each other but are defined on two different scales: insurance policy is centralized, while prevention policies are commonly designed by local jurisdictions which exert externalities on neighboring jurisdictions. In a fiscal federalism framework with perfect information, we show that, without coordination of prevention policies, collective prevention measures implemented by jurisdictions depend on the insurance system used for households and actuarial insurance does not implement optimum prevention levels. Central government can use tools based on household insurance to coordinate local collective prevention measures. Modulation of insurance premiums or deductibles combined with a transfers policy can Pareto dominate the absence of prevention policy coordination. The form of these tools depends on the insurance system. Our results call for close coordination of flood insurance and collective prevention policies.

Keywords: Insurance, Fiscal Federalism, Externalities, Prevention, Flood

JEL classification: D62, H23, Q54

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1 Introduction

Flood management embraces a wide number of areas from engineering to public policy. From an economic perspective, two issues are particularly important. The first is the level of protection that defines risk exposure and thus directly impacts individual and economic activities. The second is financial coverage of homeowners and assets. Both aspects interact with each other, and are part of a vast integrated management issue that also includes ecology and security issues (APFM, 2010). In this paper we analyze the links between flood coverage and prevention policies in a fiscal federalism framework.

Flood prevention in a community is the result of economic development on its territory and can be changed by protective infrastructures or prevention policies. Development on floodplains, deltas, and coastal areas has historically been driven by hydraulic works as observed on the Mississippi, Rhine, Nile, or Mekong rivers. Dams, levees, or "polders" (literally "diked lands") were either designed to expand the territory available for development, to provide water storage for dry seasons, or simply to protect against flooding or submersion (Fanchette, 2006). On rivers and deltas, flood protection works can modify flood exposure for other water side areas to a large degree. Indeed, dams and levees built by a jurisdiction can exert positive or negative externalities on upstream or downstream neighbors. The Three Gorges Dam in China is a typical example: it changed the entire hydraulics of the Yangtze river in its regular regime downstream as well as upstream. In the event of flooding it regulates flow in a way that is different to the systems previously in place.[1] More generally, land use choices are an important part of flood management and may change the exposure of neighboring areas. For example, soil sealing without proper design of water drainage systems can exert negative externalities, as demonstrated by the 2010 flash floods and mudslides in Madeira. The existence of such externalities calls for coordination of local prevention policies. However, in practice it is far from being the case except for large works that are the subject to important - and often controversial - impact studies. Indeed, the relevant geographical scale for collective prevention policies (the river flooding catchment area) rarely corresponds to administrative jurisdictional areas. Prevention policy coordination is therefore a key point for economic development.

The second issue is financial cover for at risk populations. In the event of disasters central governments take charge of coordinating financial solutions, particularly ex-post assistance (financial aid, conditional loans, urgent disaster rescue) for individuals and communities.

[1] See http://www.bloomberg.com/news/2010-07-20/three-gorges-dam-reports-water-flows-this-morning-that-exceed-1998-levels.html.

Some countries have set up ex-ante financing solutions including insurance systems to cover flooding. We focus on these cases in this article. Two polar examples are the French system for natural disaster coverage and the National Flood Insurance Program (NFIP) in the United States. While insurance rates are fixed by government in both systems, they are based on two different principles: uniform pricing in France and actuarial pricing with a subsidy for specific risks in the United States.[2]

Insurance and collective prevention interact with each other. On the one hand, the level of collective prevention determines the risk exposure and the level of damage insured for households. On the other hand, the type of household insurance system in place determines the risk cost borne by households. Therefore collective prevention decisions made by local jurisdictions may depend on their household insurance system. Furthermore, these two aspects are defined at different levels: insurance policy is centralized; prevention policies are commonly designed by local jurisdictions which then exert externalities on their neighbors in the same catchment area. In this context, our main question is to characterize how insurance and collective prevention policies interact. More precisely, once an insurance system has been selected, how can central government use this interaction to coordinate local collective prevention measures? Which tools based on household insurance can central government use to coordinate collective prevention policies? And what are the transfers policies that can be implemented, in a fiscal federalism framework, to compensate the costs incurred?

Over the last few decades, some countries have set up public policies to link collective prevention and insurance purchased by the population (Kunreuther, 2000). In France, prevention incentives through household insurance are based on modifying the deductible. If a jurisdiction has been affected by several natural disasters caused by the same hazard (flood, earthquake, etc.) and if no risk prevention plan has been put in place by the jurisdiction, the deductible on natural disaster insurance contracts for all households and firms in the area of the jurisdiction is significantly increased (Dumas et al., 2005). In the United States however, the policy relies on a change in premiums. Under the NFIP framework, insured households in a jurisdiction receive a rebate on their premium depending on the jurisdiction's "rating" (Burby, 2001). This rating depends on the collective risk management status: risk mapping, information, prevention and protective measures (Zahran et al., 2009).

[2] In France, insurance against natural disasters is a compulsory guarantee in standard housing insurance. Flood insurance in the United States is an independent contract. It is compulsory for individuals with a mortgage.

Insurance literature has mainly studied insurance and protection at the individual level. Picard (2008) addresses the issue of the equity-efficiency tradeoff for natural disaster coverage in the absence of externalities: prevention incentives using insurance generate strong inequalities between individuals with different types of risk and prevention costs, but actuarial insurance combined with tax transfers overcomes this tradeoff. Other studies account for externalities due to individual self-protection. Hofmann (2007) investigates the case of a monopolistic insurer and shows that under imperfect information it can reach the social optimum by engaging in price discrimination. Muermann and Kunreuther (2008) consider positive externalities and analyze the under investment in prevention in the absence of coordination between individuals. They point out that limited insurance coverage through either deductible or "at-fault" insurance can improve welfare.

Collective prevention has been less studied in the way it interacts with insurance decisions. Picard (2008) focuses on the implantation of risk management plans at a jurisdictional level in the absence of externalities. The author finds that government can provide efficient prevention incentives by offering tax reductions to high risk categories and subsidies to communities that implement a risk management plan. We differ from that study by using a fiscal federalism perspective (see Oates (1999) for a review), considering prevention as a public good. Crucial questions as to the relationship between central government and various administrative levels have been addressed in a theoretical approach (Gilbert and Picard, 1996) in the presence of spillovers due to local projects, such as transboundary pollution (Silva, 1997) or environmental dumping (Ulph, 2000). In his PhD thesis Lünenbürger (2006) studies more specifically the case of flood management in Germany. In a fiscal federalism framework, he introduces prevention as a public good in the presence of unidirectional externalities with no insurance perspective.

However, to our knowledge no study has analyzed the interaction between collective prevention measures implemented by local jurisdictions and insurance purchased by households in those jurisdictions within the relevant framework of fiscal federalism. Our main contribution to the literature is to consider public prevention policies given simple insurance schemes in a fiscal federalism framework in the presence of loss externalities between jurisdictions. In our model, central government is concerned with two issues: the choice of an insurance system to cover the risk to which households are exposed and the coordination of local collective prevention measures. The latter depends on the insurance system chosen as individuals and therefore jurisdictions do not respond the same way to different insurance contracts. We determine how, under conditions of perfect information, central government can use suitable simple modifications of household insurance contracts to provide collective prevention incentives.

Our results give interesting insights into understanding public policy on natural disasters in the presence of loss externalities. Insurance purchased by households within a jurisdiction can be based on actuarial or uniform premiums. Under complete insurance, we show that without coordination of prevention policies collective prevention measures implemented by jurisdictions are more significant if households pay an actuarial insurance premium rather than a uniform one. This is exactly why actuarial insurance does not Pareto dominate uniform insurance if externalities are strongly negative. If central government can reach the optimum via prevention tax incentives, more realistic household insurance based tools can be used to coordinate prevention policies. We show that suitable insurance premium or deductible modulation combined with a transfers policy Pareto dominates the absence of prevention policy coordination. The form of these incentives depends on the choice of insurance system and on the sign of externalities. Our results, which call for close coordination of flood insurance and collective prevention policies, are discussed from a practical public policy perspective.

The paper is organized as follows. Section 2 presents the model assumptions. It analyzes the first best choice of insurance, prevention and transfers policies, and considers the reference situation where there is no coordination between jurisdictional prevention measures. Section 3 studies prevention incentives for jurisdictions using three different tools: tax incentives, premium and deductible modulation. Section 4 discusses the results and policy implications.

2 The model

2.1 Model assumptions

Risk. We consider a watershed composed of N jurisdictions, $1 \leq j \leq N$, with a central government. In the chosen spatial representation, the jurisdictions are located next to a river modeled by a directed line.[3] Jurisdiction 1 is upstream and jurisdiction N is downstream, as shown on Figure 1.

We assume here that floods are perfectly correlated within a jurisdiction: one flood may damage all inhabitants in a jurisdiction or nobody. However, when a flood occurs next to

[3]Note that Lünenbürger (2006) chooses another specification for unidirectional externalities.

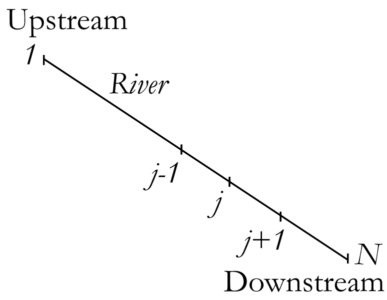

Figure 1: Spatial representation

the river, each jurisdiction may be flooded or not depending on its prevention level. We assume that the initial loss probability is the same for all jurisdictions and we denote this common probability by p^0. Jurisdiction j's final loss probability, P_j, depends on its "own" preventive measures and on jurisdiction $j-1$'s preventive measures.

Prevention and externalities. Jurisdictions can reduce their loss probabilities by implementing preventive or protective measures, henceforth called prevention, to reduce the risk exposure for all inhabitants. We denote a_j as the prevention measure, $0 \leq a_j \leq p^0$. It has a cost denoted by $C(a_j)$ which is assumed to be quadratic:

$$C(a_j) = \frac{c}{2} a_j^2, \quad c > 0. \tag{1}$$

Prevention is funded at the jurisdictional level by lump sum local taxes t_j, which do not provide prevention incentives to individuals. This assumption seems valid when considering collective rather than individual prevention.

Jurisdictions are subject to loss externalities originating from the prevention measures implemented by upstream jurisdictions. Typically, dams and levees are associated respectively with positive and negative externalities during the normal course of their operations (Tobin, 2007). A dam built by an upstream jurisdiction protects the downstream ones from flooding. On the other hand, an upstream levee increases the downstream flow. In the event of dam or levee failures, negative externalities are exerted downstream as a failure causes a large increase in velocity and flow rate. Soil sealing also exerts negative externalities on neighboring jurisdictions. Indeed, externalities correspond to complicated physical and mechanical phenomena, and are difficult to model due to the diversity of situations.

We use e to denote the externalities coefficient. For the sake of simplicity, we assume that[4]

$$P_j(a_j, a_{j-1}) = \begin{cases} p^0 - a_1 & \text{for } j = 1, \quad (2) \\ p^0 - a_j - ea_{j-1} & \text{for } j \in [\![2; N]\!]. \quad (3) \end{cases}$$

We assume that $-1 \leq e \leq 1$ as we suppose that one's own prevention has a higher impact on one's risk level than the neighboring prevention. This assumption guarantees that prevention levels are positive. If $e > 0$, the prevention measures that may be implemented by jurisdiction $j-1$ reduce jurisdiction j's final loss probability. Thus, $e > 0$ corresponds to positive externalities and $e < 0$ to negative ones. The form chosen for externalities implies that the downstream local authority j cannot reduce the impact of the externalities generated by its upstream neighbor $j-1$ using its own prevention measures.[5] A particularity of a river system is that two jurisdictions have a specific role: jurisdiction 1, which is not subject to externalities, and jurisdiction N, which does not exert any externality. These geographic heterogeneities have to be taken into account in the design of prevention incentives.

Jurisdictions. Each jurisdiction consists of a population of individuals normalized to 1. Prevention reduces the loss probability for all individuals. Therefore risks are perfectly correlated within a jurisdiction: with probability P_j, all individuals in a jurisdiction are simultaneously flooded or nobody is. This is why we consider one representative individual with an income I, exposed to a loss L.[6] We assume that $cp_0 \geq 4L$ to ensure all loss probabilities are positive.

Individual preferences. Preferences of the representative individual in jurisdiction j are described by a common utility function $u(x_j)$ where x_j is the private good consumption. We assume that individuals are risk averse and therefore that $u(\cdot)$ is increasing and concave. Individuals value externalities by their impact on losses.

State insurance. We assume that all households must purchase insurance and that it is only offered by central government. State insurance is assumed to be risk neutral. This model only represents a river catchment area, i.e. a set of N "connected" jurisdictions

[4]This expression is different from the one used by Hofmann (2007) and Muermann and Kunreuther (2008). Both papers assume that a loss directly caused by an agent and a loss indirectly caused via others are independent.

[5]We do not consider externalities exerted on jurisdictions further downstream as it would not change the results.

[6]Considering different losses among households within a jurisdiction and allowing transfers between them would only change the results under incomplete insurance.

among which risks are correlated. However, at the national level, the number of watersheds enables risk tolerance by central government to be increased as well as risk to be diversified. The insurance premium can be either actuarial $(\Pi_j^a)_{1\leq j\leq N}$ or uniform Π^u. In both cases, the premium depends on the prevention measures taken by the different jurisdictions.

$$\Pi_j^a(a_j, a_{j-1}) = P_j(a_j, a_{j-1})L, \tag{4}$$

$$\text{or } \Pi^u(a_1, ..., a_N) = P^u(a_1, ..., a_N)L \text{ with } P^u(a_1, ..., a_N) = \frac{1}{N}\sum_{1\leq i\leq N} P_i(a_i, a_{i-1}). \tag{5}$$

The actuarial premium for the inhabitants of jurisdiction j is a function of a_j and a_{j-1} and the uniform premium is a function of all a_j. Insurance is not systematically complete. If not, the deductible, denoted by D, is lower than the potential loss ($D < L$).

Finally, central government allows transfers between jurisdictions. We do not analyze inequalities nor redistribution effects, either inside jurisdictions or between them.

Timing. Central government and jurisdictions have perfect information. The timing of the model is as follows.

Stage 1: Central government chooses the insurance system, the form of the prevention incentives and the transfers policy between jurisdictions.

Stage 2: Jurisdictions determine their prevention levels.

Finally, the state of Nature is realized: losses are revealed and each individual knows its final wealth. Central government decides the form of the incentives before jurisdictions set their prevention levels. As in Hofmann (2007) and Muermann and Kunreuther (2008), in Stage 2 we consider the Nash equilibrium. We study the three forms of incentive: tax incentives for jurisdictions, premium modulation and deductible modulation of household insurance contracts. First, we assume that insurance is complete.

2.2 Centralization

We consider here the first best situation, where central government decides the type of insurance system and the prevention levels. Under complete insurance - actuarial ($s = a$) or uniform ($s = u$) - and in the presence of transfers, the central government program is to maximize the total wealth of the representative individuals:

$$\begin{array}{l} \max\limits_{a_j} \sum\limits_{1\leq i\leq N} W_i = \sum\limits_{1\leq i\leq N} I - \Pi_i^s - t_i^s, \\ u.c.\ \forall i,\ t_i^s \geq \frac{c}{2}(a_i^s)^2. \end{array} \tag{6}$$

This leads to the following proposition.

Proposition 1. *Under centralization, the prevention levels that lead to the highest social welfare are the following:*

$$a_j^{**} = \begin{cases} (1+e)\dfrac{L}{c} & \forall j \in [\![1; N-1]\!], \\ \dfrac{L}{c} & \text{for } j = N. \end{cases} \tag{7}$$

Under complete insurance, these do not depend on the insurance system in place.

These prevention levels internalize externalities exerted by jurisdictions 1 to $N-1$. Under complete insurance, they do not depend on the given insurance system whether actuarial or uniform. Indeed, the sum of expected losses supported by the jurisdictions only depends on the prevention measures and does not depend on the way the financial burden for flood losses is shared between jurisdictions. However, the systems do not lead to the same wealth in each jurisdiction. This is due to geographic heterogeneities between jurisdictions in the model.

However, in practice central government can rarely enforce prevention constraints on jurisdictions. Even if legal sanctions exist, these may not have the desired preventive effect on jurisdictions. For example, in the United States, states can be sued if protection measures are not implemented: "the Legislature approved \$500 million in settlements of claims in 2005 for failed levees in the 1986 and 1997 floods" against the state of California (California Hearing, 2005).

2.3 In the absence of prevention policy coordination (autarky)

We consider as a reference situation the case where all jurisdictions choose their prevention levels under a given insurance system and where there is no coordination between their prevention policies. Indeed, once an insurance system has been put in place by central government, it is difficult to modify it. This is called "autarky".

Each jurisdiction maximizes the wealth of its representative individual W_j^s either under actuarial insurance ($s = a$) or under uniform insurance ($s = u$).

$$\begin{aligned} &\forall j \in [\![1; N]\!],\ \max_{a_j} W_j^s = I - \Pi_j^s - t_j^s \\ &u.c.\ \ t_j^s \geq \tfrac{c}{2} a_j^2. \end{aligned} \tag{8}$$

Under actuarial insurance this leads to the following prevention measures:

$$\forall j \in [\![1; N]\!],\ a_j^{a*} = \frac{L}{c}. \tag{9}$$

The prevention levels do not internalize externalities exerted on the downstream jurisdiction as in Muermann and Kunreuther (2008) and Hofmann (2007), since actuarial insurance does not give any price signal on these. This is why centralization leads to higher prevention levels than in autarky if and only if externalities are positive. Note that if there are no externalities, actuarial insurance leads to optimum prevention levels under autarky.

$$\forall j \in [\![1; N]\!],\ a_j^{**} > a_j^{a*} \Leftrightarrow e > 0. \tag{10}$$

As an illustration of negative externalities, under autarky a jurisdiction may build a higher levee than would be socially optimum. This measure reduces its own risk. However, in the event of flooding or levee failure, it increases the risk for neighboring jurisdictions. In the case of the Missouri floods in 1993, some landowners had built higher levees than authorized to protect their crops. Therefore they put other developed land nearby at risk (Rasmussen, 1999).

Under uniform insurance the situation is different as it induces two opposite effects. The uniform premium provides a price signal on the direct impact of prevention as well as on the externalities created - except for the downstream jurisdiction which does not exert any externality. However, the signal on these impacts is diluted since the uniform premium shares the total cost of risk and externalities between all jurisdictions. The factor $\frac{1}{N}$ that appears in the expression for the prevention measures reflects this *dilution effect*:

$$a_j^{u*} = \begin{cases} \left(\dfrac{1+e}{N}\right)\dfrac{L}{c} & \text{for } j \in [\![1; N-1]\!], \\ \dfrac{1}{N}\dfrac{L}{c} & \text{for } j = N. \end{cases} \tag{11}$$

Because of the dilution effect, prevention levels are lower than those that would be implemented by central government under centralization:

$$\forall e,\ \forall j \in [\![1; N]\!],\ a_j^{**} > a_j^{u*}. \tag{12}$$

Comparing the two insurance systems. Under autarky, the difference between prevention measures under actuarial and uniform insurance arises from the dilution effect. Indeed, the impact of a marginal increase in jurisdictional prevention on the premium is quite different: it decreases the actuarial premium by 1 and the uniform premium by only $\frac{1+e}{N}$ ($\frac{1}{N}$ for jurisdiction N). Therefore the prevention measure is of more benefit and so greater in the case of actuarial insurance:

$$\forall j \in [\![1; N]\!], \quad a_j^{a*} > a_j^{u*}. \tag{13}$$

A comparison of the different prevention measures is summarized in Figure 2.

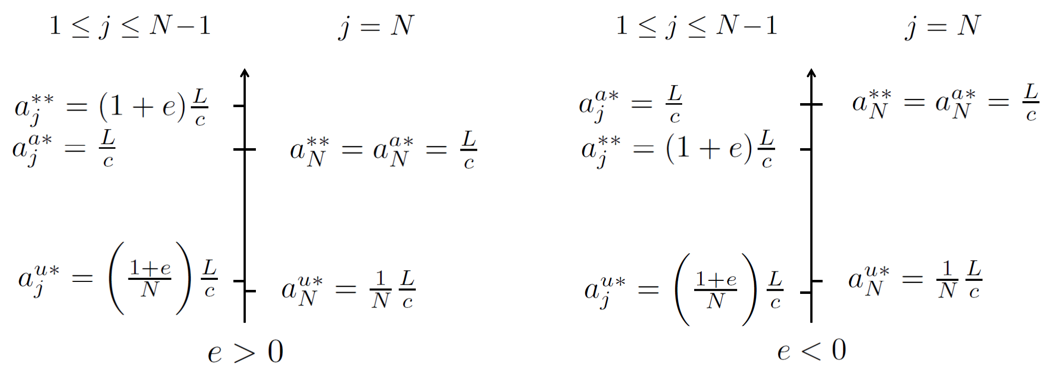

Figure 2: Ranking of the different prevention measures

This last comparison (see Equation 13) between prevention measures under actuarial and uniform insurance in autarky leads to the following proposition.

Proposition 2. *Under autarky and under complete insurance, actuarial insurance leads to more prevention than uniform insurance. However, actuarial insurance may not Pareto dominate uniform insurance. For high values of N:*

- *if externalities are positive or not too negative ($e \geq -\frac{1}{2}$), actuarial insurance Pareto dominates uniform insurance;*
- *if externalities are strongly negative ($e < -\frac{1}{2}$), all jurisdictions, except for the upstream one, are better off under uniform insurance.*

Proof. See Appendix. □

If externalities are positive, actuarial insurance which induces more prevention makes all jurisdictions better off for high values of N. Clearly, if negative externalities are very significant, actuarial insurance which leads to higher prevention levels is not desirable except for the upstream jurisdiction 1 which is not subject to externalities. This illustrates the *general theory of second best* formalized by Lipsey and Lancaster (1957): "it is not true that a situation in which more, but not all, of the optimum conditions are fulfilled is necessarily, or is even likely to be, superior to a situation in which fewer are fulfilled". In the absence of externalities, actuarial insurance leads to optimum prevention levels and uniform insurance does not. However, in the presence of externalities, under some conditions uniform insurance Pareto dominates actuarial insurance.

Comparing autarky with centralization. In autarky, the prevention levels are not optimum. However, raising them would reduce the welfare of some jurisdictions. To avoid this, central government can organize transfers between jurisdictions. This is why we compare autarky with the situation where central government implements the first best prevention levels and simultaneously designs a transfers policy. There is a Pareto dominance of centralization if no jurisdiction is worse off with central government transfers and if central government budget constraint is satisfied.

Proposition 3. *Under actuarial or uniform complete insurance, for all values of e, there exists a transfers policy $(T_j)_{1\leq j\leq N}$ such that centralization Pareto dominates autarky.*

Proof. See Appendix. □

In a situation where prevention policies are decentralized at the jurisdictional level, central government has to consider applying prevention incentive measures to jurisdictions.

3 Prevention incentives

In this section we study three types of policies to encourage collective prevention: tax incentives for local jurisdictions, premium modulation and modulation of deductibles in the case of uniform insurance.

3.1 Tax incentives for local jurisdictions

We consider the case where central government coordinates prevention policies by setting up tax incentives for local jurisdictions. We define $\tau_j(a_j)$ as the tax paid by jurisdiction j to central government. For the sake of simplicity, we focus on linear taxes depending on collective prevention, with coefficient τ_j^a in the actuarial case and τ_j^u in the uniform case.

$$\forall j \in [\![1; N]\!],\ \tau_j(a_j) = -\tau_j^s a_j. \tag{14}$$

Government anticipates the reactions of jurisdictions when choosing the form of tax incentives under a given insurance system. We solve this game backward. We first consider jurisdictional wealth maximization for a given incentive policy:

$$\forall j \in [\![1;N]\!], \begin{cases} \max\limits_{a_j} W_j^a = I - \Pi_j^s(a_1,...,a_N) - t_j, \\ u.c.\ \ t_j \geq \frac{c}{2}a_j^2 + T_j - \tau_j^s a_j. \end{cases} \tag{15}$$

We obtain the prevention measure as a function of incentive level $a_j(\tau_j^s)$ (see proof in the Appendix for the detailed calculation). Knowing the reaction of local jurisdictions to its incentive policy, government then maximizes social welfare subject to its budget constraint:

$$\begin{cases} \max\limits_{\tau_i^s} \sum\limits_{1\leq i\leq N} W_i^a = \sum\limits_{1\leq i\leq N} \left[I - \Pi_i^s(a_1(\tau_i^s),...,a_N(\tau_i^s)) - \frac{c}{2}a_i(\tau^s)^2 - T_i + \tau_i^s a_i(\tau_i^s) \right], \\ u.c. \quad \sum\limits_{1\leq i\leq N} T_i - \tau_i^s a_i(\tau_i^s) \geq 0. \end{cases} \tag{16}$$

This leads to the following result.

Proposition 4. *In the centralized case, central government can implement prevention levels and welfare by using linear tax incentives. There is a transfers policy* $(T_j)_{1\leq j\leq N}$ *such that a tax incentive policy Pareto dominates autarky.*

- *Under actuarial complete insurance, these tax incentives have the following form:*

$$\tau_j^a = \begin{cases} eL & \forall j \in [\![1;N-1]\!], & (17) \\ 0 & for\ j = N. & (18) \end{cases}$$

- *Under uniform complete insurance,*

$$\tau_j^u = \begin{cases} (1+e)\dfrac{N-1}{N}L & \forall j \in [\![1;N-1]\!], & (19) \\ \dfrac{N-1}{N}L & for\ j = N. & (20) \end{cases}$$

Proof. See Appendix. □

This form of incentives corresponds to a Pigouvian tax. It leads to the first best prevention measures and we show that this tax scheme combined with a suitable transfers policy Pareto dominates autarky. As the prevention levels in autarky depend on the insurance system, but not the optimum prevention levels, the form of the tax incentives depends on the insurance system. Note that in the end only two different coefficients are required: one for the jurisdictions $1 \leq j \leq N-1$ which exert loss externalities and one for N.

Under actuarial insurance, the marginal tax rate reflects the internalization of the externalities exerted by each jurisdiction on its downstream neighbor. As centralization leads to higher prevention levels than in autarky if and only if externalities are positive (see Equation 10), these taxes consistently generate a reward for collective prevention if and only if externalities are positive ($\forall j,\ \tau_j^a > 0 \Leftrightarrow e > 0$). As jurisdiction N does not exert any externality, tax incentives are not relevant for it.

Under uniform insurance, the marginal tax rate takes into account both the direct benefits of prevention on the considered jurisdiction and the externalities exerted, since the uniform premium only gives a diluted price signal on risk and loss externalities. Taxes are a reward for collective prevention whatever the sign of the externalities, since, under uniform insurance, in autarky prevention levels are lower than optimum (see Equation 12).

In practice, such taxes could not be easily implemented on a large scale. Indeed, the assumption that central government is able to differentiate tax rates between jurisdictions that exert flood loss externalities and those that do not is not realistic. It would require perfect knowledge about the different situation of the various jurisdictions. However, interestingly enough this result can be used to better understand some situations at the catchment area level, where a number of jurisdictions have to jointly consider construction of new prevention infrastructure or repair of existing facilities. In the United States, for example, after three very large floods occurred over a four year period, in May 2010 the county of Pierce (Washington) published a county ordinance establishing a flood control zone district. As the county council has taxation authority, this could be used to set up a tax to fund renovation or rebuilding flood protection infrastructure. However, not all cities in the county are at risk and the creation of such a tax (which is not currently planned) is a subject of debate since it seems unfair to those who would not benefit from the work.[7]

3.2 Modulation of household insurance contracts

We now consider more realistic collective prevention incentives that do not differentiate between jurisdictions. These incentives are based on household insurance.

3.2.1 Modulation of household insurance premiums

Central government coordinates collective prevention measures at the jurisdictional level by setting up a household insurance premium modulation system. As insurance is complete, this corresponds to an increase (penalty) or a decrease (reward) in the premium depending on the collective prevention measures implemented.

[7] See http://www.miltonedgewoodsignal.com/article/2086.

We denote by Γ_j the increase in the premium paid by the representative individual in jurisdiction j. That is, $\Gamma_j(a_j) > 0$ corresponds to a penalty. For the sake of simplicity, we consider a linear premium modulation.

$$\forall j \in [\![1; N]\!],\ \Gamma_j(a_j) = -\gamma^s a_j. \tag{21}$$

The principle is actually equivalent to the linear tax incentives previously studied except the premium modulation does not distinguish between jurisdictions: there is one unique γ. The final premium paid by an individual in jurisdiction j will be $\Pi_j^a - \gamma^a a_j$ in an actuarial system and $\Pi^u - \gamma^u a_j$ in a uniform system.

To obtain the optimum level of modulation, we proceed by backward induction in the same manner as for the conditional taxes. We first compute the optimum levels of prevention in each jurisdiction considering a given γ^a or γ^u. Then central government, with knowledge of jurisdictional prevention measures, maximizes social welfare subject to its budget constraint. This leads to the following corollary.

Corollary 1. *Under complete (actuarial or uniform) insurance, central government can improve social welfare by using linear modulation of household insurance premiums.*

- *Under actuarial insurance, there exists a transfers policy $(T_j)_{1\leq j\leq N}$ such that premium modulation Pareto dominates autarky. Under actuarial insurance, the modulation coefficient is*
$$\gamma^a = \frac{N-1}{N} eL. \tag{22}$$

- *Under uniform insurance, for high values of N, there exists a transfers policy $(T_j)_{1\leq j\leq N}$ such that premium modulation Pareto dominates autarky.*

$$\gamma^u = \frac{N-1}{N^2}\Big[(1+e)(N-1)+1\Big]L. \tag{23}$$

Proof. See Appendix. □

As the form of premium modulation cannot be differentiated between jurisdictions, it does not implement the prevention levels and welfare obtained in the centralized case. Otherwise the interpretation of these results is quite similar to the tax case. The form of premium modulation depends on the insurance system initially chosen. Under uniform insurance, this policy consists of a reward, since under autarky jurisdictions perform less prevention than recommended, again due to the dilution effect. Under actuarial insurance, this premium modulation consists of a reward if and only if externalities are positive.

If externalities are negative, the individual premium increases with respect to collective prevention. Setting up this policy may therefore raise sensitive issues, since collective prevention which reduces a jurisdiction's "own" risk would be penalized by state insurance.

In reality, different types of collective prevention can be implemented simultaneously. The prevention proxy could then correspond to a rating, as in the United States. NFIP policyholders benefit from a rebate on their premium depending on their jurisdiction's collective prevention rating that includes four types of prevention measures: *public information, mapping and regulations, flood damage reduction, and flood preparedness.* These can earn respectively as much as 6.3%, 39.7%, 45%, and 9% of the points that make up the maximum grading (NFIP, 2006). The more collective prevention that is implemented, the higher the percentage rebate on initial individual premiums. Implementation of such a policy is significantly complicated by the fact that some types of collective prevention do not exert any loss externality (preventive information, crisis management) and some may impact downstream neighbors in a positive way (dams, retention basins) or in a negative way (levees). The rating should reflect whether prevention measures are coordinated at the relevant geographical level, for example the catchment area level.

3.2.2 Modulation of household insurance deductibles under uniform insurance

Considering complete insurance is a major restriction. Incomplete insurance is much more realistic. We focus on the case where central government has selected a uniform insurance system for political and historical reasons, as in France for example. In this case, under perfect information, incomplete insurance can provide prevention incentives. The approach is different from the usual one, where, under imperfect information, setting up deductibles aims to obtain information on the risk exposure of the insured. Deductible modulation as an incentive for individual prevention has already been studied in the case of uniform insurance (Latruffe and Picard, 2005) and actuarial insurance with externalities (Muermann and Kunreuther, 2008). In our model, under uniform insurance, central government introduces deductibles. Therefore jurisdictions have more incentives for collective prevention, as their risk averse inhabitants prefer to reduce the amount of risk that they bear.

We assume that the deductible D depends on the jurisdiction's prevention measures. More precisely, we choose $D(a_j) = \delta(p^0 - a_j)$ and assume to be near full insurance ($0 \leq \delta << 1$). Under incomplete insurance, the representative individual in jurisdiction j has differing wealths between a loss situation (W_j^L) and in the absence of loss (W_j^{NL}). Hence jurisdiction

j's program becomes

$$\forall j \in [\![1;N]\!], \quad \max_{a_j} \quad P_j(a_j,a_{j-1})u(W_j^L)+(1-P_j(a_j,a_{j-1}))u(W_j^{NL}), \tag{24}$$

$$\text{with } W_j^L = I-\Pi_D^u(a_1,...,a_N)-D(a_j)-\frac{c}{2}a_j^2-T_j,$$

$$W_j^{NL} = I-\Pi_D^u(a_1,...,a_N)-\frac{c}{2}a_j^2-T_j.$$

The uniform premium also depends on the deductible amount and

$$\Pi_D^u(a_1,...,a_N)=\frac{1}{N}\sum_{1\le j\le N}P_j(a_j,a_{j-1})(L-D(a_j)).$$

Proposition 5. *Under uniform insurance, for high values of N, for all e, introducing household insurance deductibles that decrease linearly with respect to collective prevention induces higher prevention levels than under autarky. Central government can improve social welfare by using linear modulation of the deductible, and a small deductible modulation Pareto dominates autarky.*

Proof. See Appendix. □

The deductible modulation consists of a reward for collective prevention whatever the sign of the externalities since under autarky prevention levels are lower than the optimum (see Equation 12). This reward is operative: all prevention levels increase. Without implementing optimum prevention levels, this policy can partially correct the under-investment in prevention due to the dilution effect whatever the sign of the externalities. A small deductible modulation enhances social welfare and Pareto dominates autarky.

Several practical aspects of such a policy need to be discussed. In France, insurance is uniform and household insurance deductibles depend on a risk prevention plan being laid down by the jurisdiction - that is on the decision to implement such a plan.[8] While this policy seems to have an effect in jurisdictions where repeated losses occur, it does not appear to be a sufficient incentive for collective prevention, because of the low level of the deductibles and the ex-post nature of this measure. In addition the deductible modulation introduced in 2000 created a windfall effect. As long as the prevention plan was in the process of being implemented, the jurisdiction's inhabitants saw their deductibles unchanged. A plan can take several years to be implemented, since it may require hydrological studies.[9]

[8]These plans merely correspond to a risk assessment inside the community at a given time. They do not assess the development of prevention measures through time (as opposed to that which is performed in the United States).

[9]According to the circular of January, 21 2004 on management of urbanization and adapting buildings to flood plains, flood prevention plans last three years on average.

If after five years the plan had still not come into effect, then deductibles increased at that point. Many jurisdictions put forward numerous plans which were not finalized (Letrémy, 2009). In 2003, to limit this effect, the lead time for implementing prevention plans was reduced to four years.

4 Discussion and policy implications

Our model relies on simple assumptions and throws light on the interaction mechanism between collective prevention and household insurance. A pragmatic approach requires consideration of other aspects for proper design of public policies. Here, our results are discussed with respect to policy implications and concrete flood management aspects.

Our model points out that the type of household insurance contract directly impacts collective prevention measures. This corresponds to the fact that jurisdictional prevention measures, as decided for example at the city or county level, depend on the price signal given by household insurance. As tested by Laury and McInnes (2003), insurance can provide a risk price signal, although objective risk can be distorted through the use of loading factors or special policy premiums (Kunreuther and Pauly, 2004).[10] Our model shows that insurance policy is not neutral for collective prevention measures and therefore for the design of collective prevention policies. If central government can reach the optimum via prevention tax incentives, more realistic tools based on household insurance can be used to coordinate prevention policies. Premium and deductible modulations under uniform insurance can increase social welfare without reaching optimum prevention levels. We stress that these incentives should depend on the insurance system - actuarial or uniform - and on the externalities exerted by collective prevention. In practice, the price signal should be sufficiently important to have an impact on risk perception, but within the limits of household budgetary capabilities.

Our results enhance the importance of integrating externalities in the evaluation of prevention measures if these are used as a proxy for taxation or insurance based prevention incentives. Risk managers, and particularly engineers, have known for a long time the importance of integrating collective prevention externalities when designing flood control systems. For example, in the Netherlands, construction or maintenance of "polders" have been preformed by the "waterschappen" (local water communities) since the 18th century. Because of the numerous legal disagreements between polders due to their induced negative

[10]Note that other signals may be designed. In France every new owner or renter receives notification of the risk zone and past natural disasters that have occurred to his future dwelling.

externalities - typically soil removed to strengthen levees -, the “waterstaat” (central water administration) was created in 1798 to coordinate all these local activities. Engineers can also recommend prior removal of land or compensation for neighboring inhabitants. For example, in France, some projects include initial compensation to neighboring inhabitants for disturbance, loss of real estate value and also the determination of ex-post compensation for flooding.[11] Our results strengthen the importance of taking into account the existence of such externalities in any prevention evaluation that might be used as the basis of a tax or insurance modulation.

Our model could be easily extended to the national level with several watersheds. In our simple setting, centralization would still lead to optimum prevention levels. However, this creates new issues, such as the question of what is the right decision making level for prevention measures. In a first approximation, in many countries prevention measures are taken at the local level. However, in practice, flood management can involve many administrative levels. This is quite logical as watersheds from small rivers are included in watersheds of large rivers that cross over into many more local jurisdictions. In Germany for example, local government, the *Bundesland* and the Federal Government are each responsible for some flood prevention measures (Lünenbürger, 2006). When defining the correct decision making level, asymmetric information between government and jurisdictions has to be taken into account. Indeed, it could be argued that government has better information on the externalities while local jurisdictions possess better information on the cost of risk or prevention. Under such incomplete information, as shown by Gilbert and Picard (1996) in the general case of producing public goods and by Ulph (2000) in the case of environmental damages, the optimum decision making level arises from a tradeoff between the capacity to internalize externalities at the central level and knowledge of prevention costs or risk at the local level. While still considering insurance as a central government policy, an extension of our model with imperfect information could draw results that relate to the optimum level of prevention decision making.

Information is not the only issue linked to decision making level. Local entity interests may differ from central government. At a local level, mayors may face a tradeoff between prevention - to protect people and goods - and economic development or limiting pressure from real estate.[12] In France for example, negotiations between central and local governments in the framework of natural risk prevention plans are difficult. This explains

[11] An example is the dynamic reduction in flooding of the Meuse at Mouzon in France (Chambre d’Agriculture des Ardennes, 2006).

[12] This corresponds to what Burby (2006) introduces as the *local government paradox*.

why some of these plans are delayed or abandoned. The reluctance of mayors to enforce prevention policies is particularly problematic under uniform insurance, as individuals do not obtain risk information via their premium. This was highlighted by the controversy following Storm Xynthia in France on February 28, 2010 which caused the death of 47 people, 29 of whom lived below the levee that failed.

Furthermore, mobility and timing issues also greatly complicate the design of prevention policies. An interesting extension could certainly be to develop our model in a Tiebout framework (Tiebout, 1956), where people select their locality depending on their collective prevention preferences. Such a mobility framework has been studied in the environmental economics literature by Silva (1997) that looks at transboundary pollution with population crowding as an externality. The author shows that decentralized control of transboundary pollution can be efficient since pollution abatements or interregional transfers are entry fees that limit the negative effects of population crowding. However, setting up the appropriate prevention is difficult for local or central governments when confronted with the housing or investment dynamic decisions of agents. First, the level of protection increases with private capital exposure. This government reaction to protect exposed capital can be anticipated by agents, as studied by Kydland and Prescott (1977). They quote the specific case of floods: “the rational agent knows that, if he and others build houses there [on a flood plain], the government will take the necessary flood-control measures”. Second, if the level of protection increases with private capital exposure, collective protection reciprocally attracts more investment, as modeled by Kousky et al. (2006). Protection decisions may induce a higher risk exposure.[13] Introducing such a dynamic framework in a model with location choices would be interesting but probably complex.

Prevention may not only increase risk exposure, but also distort individual risk perception, an issue we do not address in the model. For example, White (1942) underlines that there may be a false sense of security behind levees which modifies flooding risk perceptions. Indeed, insurance and prevention policies are linked all the more closely because of the impact they have on the risk perception on which they depend. In that framework, voluntary insurance - as in the United States - also opens new issues which we have not addressed, since our model considers compulsory insurance as in France. First, risk perception impacts the demand for insurance. Second, under voluntary insurance, the prevention level

[13]This effect is called the *safe development paradox* by Burby (2006). R. Burby illustrates the case of the New Orleans flooding where “federal actions consisted primarily of funding hurricane protection levees and other flood control works to promote urban development in the “protected” areas and the provision of flood insurance at subsidized rate”. To prevent this phenomenon, French risk prevention plans closely monitor new construction in exposed areas. See `http://www.risquesmajeurs.fr/les-plans-de-prevention-des-risques-naturels-ppr`.

may have a reverse effect on insurance penetration: more protection lessens the cost of risk and thus may increase insurance penetration as was argued in the United States. While Zahran et al. (2009) find a relationship between the prevention levels at NFIP communities and their insurance penetration rates, they do not address causality: does insurance induce more prevention or does prevention induce more insurance? The impact of this US policy is unclear and merits more in depth analysis.

Designing coverage and prevention policies for natural disasters and especially for floods is indeed a complex issue. Our model, by using clear and simple assumptions, clarifies the interaction between insurance and prevention and reinforces the importance of coordinating insurance and prevention policies. Due to its simplicity, this model could interestingly be used in future research to explore the interaction between insurance and prevention while complicating the decision making pattern in a fiscal federalism framework, by considering mobility issues in a dynamic setting or by studying voluntary insurance.

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Appendix

A. Proof of Proposition 2

Under actuarial insurance, in autarky, jurisdiction j's wealth is

$$W_j^{a*} = \begin{cases} I - p^0 L + \frac{1}{2}\frac{L^2}{c} & \text{for } j = 1 \\ I - p^0 L + \left(\frac{1}{2} + e\right)\frac{L^2}{c} & \forall j \in [\![2; N]\!]. \end{cases}$$

Under uniform insurance, in autarky, jurisdiction j's wealth is

$$W_j^{u*} = \begin{cases} I - p^0 L + \left(N - \frac{3}{2}\right)\left(\frac{1+e}{N}\right)^2 \frac{L^2}{c} + \frac{L^2}{cN^2} & \forall j \in [\![1; N-1]\!], \\ I - p^0 L + (N-1)\left(\frac{1+e}{N}\right)^2 \frac{L^2}{c} + \frac{1}{2}\frac{L^2}{cN^2} & \text{for } j = N. \end{cases}$$

We assume that $N >> 1$,

$$\begin{aligned} j = 1,\ W_1^{a*} - W_1^{u*} &= \frac{1}{2}\frac{L^2}{c}, \\ \forall j \in [\![2; N]\!],\ W_j^{a*} - W_j^{u*} &= \left(\frac{1}{2} + e\right)\frac{L^2}{c}. \end{aligned}$$

Thus,

$$j = 1, \qquad \forall e,\ W_1^{a*} > W_1^{u*}, \tag{25}$$
$$\forall j \in [\![2; N]\!], \qquad W_j^{a*} \geq W_j^{u*} \Leftrightarrow e \geq -\tfrac{1}{2}. \tag{26}$$

In the case of low values of N, this is not always true: actuarial insurance may not Pareto dominate uniform insurance for positive externalities. Indeed, the *dilution effect* is not of consequence. The prevention levels for downstream and upstream jurisdictions may be consequent in the case of uniform insurance, and the uniform premium may be lower than the actuarial one. For example, in the case of positive externalities $e = 1$, and $N = 2$: $a_1^{a*} = a_2^{a*} = a_1^{u*} = L/c$, $a_2^{u*} = L/(2c)$, $\Pi_1^a = p^0 L - L^2/c$, $\Pi_2^a = p^0 L - 2L^2/c$, and $\Pi^u = p^0 L - 5L^2/(4c)$. Thus $W_1^{a*} < W_1^{u*}$ and $W_2^{a*} > W_2^{u*}$. □

B. Proof of Proposition 3

With and without coordination of prevention policies under actuarial insurance. Under actuarial insurance, in the centralized case, jurisdiction j's wealth corresponds to the wealth level reached when performing prevention measure a_j^{**} under the transfer system set up by central government. Thus final wealth levels are:

$$W_j^{a**} = \begin{cases} I - p^0 L + (1+e)\frac{L^2}{c} - \frac{(1+e)^2}{2}\frac{L^2}{c} - T_1 & \text{for } j = 1 \\ I - p^0 L + \frac{(1+e)^2}{2}\frac{L^2}{c} - T_j & \forall j \in [\![2; N-1]\!], \\ I - p^0 L + \left[\frac{1}{2} + e(1+e)\right]\frac{L^2}{c} - T_N & \text{for } j = N, \end{cases} \tag{27}$$

The centralized case Pareto dominates autarky if all jurisdictions are better off and the central budget constraint is verified. This leads to the following constraints system, with at least one of the N first inequalities strictly satisfied:

$$\begin{cases} W_1^{a**} - W_1^{a*} = -\frac{e^2}{2}\frac{L^2}{c} - T_1 \geq 0 & \text{for } j = 1, & (28) \\ W_j^{a**} - W_j^{a*} = \frac{e^2}{2}\frac{L^2}{c} - T_j \geq 0 & \forall j \in [\![2; N-1]\!] \ , & (29) \\ W_N^{a**} - W_N^{a*} = e^2\frac{L^2}{c} - T_N \geq 0 & \text{j=N}, & (30) \\ \sum_{1\leq j\leq N} T_j \geq 0. & & (31) \end{cases}$$

If $\forall j,\ T_j = 0$, the first condition only is not satisfied. Clearly, as soon as $N \geq 3$, there exists a system of transfers $(T_j)_{1\leq j\leq N}$ such that all conditions are satisfied. For example, $T_1 = \frac{e^2}{2}\frac{L^2}{c}$; $T_2 = T_3 = \frac{e^2}{4}\frac{L^2}{c}$; $\forall j \geq 4,\ T_j = 0$. Therefore centralization Pareto dominates autarky for any value of $e \neq 0$. If $e = 0$, actuarial insurance in autarky leads to the optimum prevention measures.

With and without coordination of prevention policies under uniform insurance.
Under uniform insurance, in the centralized case, jurisdiction j's wealth is

$$W_j^{u**} = \begin{cases} I - p^0 L + \frac{N-2}{2}\frac{(1+e)^2}{N}\frac{L^2}{c} + \frac{L^2}{cN} - T_j & \forall j \in [\![1; N-1]\!], \\ I - p^0 L + (N-1)\frac{(1+e)^2}{N}\frac{L^2}{c} + \frac{L^2}{cN} - \frac{1}{2}\frac{L^2}{c} - T_N & \text{for } j = N. \end{cases}$$

The centralized case Pareto dominates autarky if all jurisdictions are better off and the central budget constraint is verified. This leads to the following constraints system, with at least one of the N first inequalities strictly satisfied:

$$\begin{cases} W_j^{u**} - W_j^{u*} = \left[\frac{N-1}{N} + (1+e)^2\left(\frac{N}{2} - 2 + \frac{3}{2N}\right)\right]\frac{L^2}{cN} - T_j \geq 0 & \forall j \in [\![1; N-1]\!], & (32) \\ W_N^{u**} - W_N^{u*} = \left(\frac{N-1}{N}\right)^2\left[(1+e)^2 - \frac{1}{2}\right]\frac{L^2}{c} - T_N \geq 0 & \text{for } j = N, & (33) \\ \sum_{1\leq j\leq N} T_j \geq 0. & & (34) \end{cases}$$

There exists a transfer scheme if $1 + (1+e)^2(N-1) > 0$. As this condition is always verified, there exists a system of transfers $(T_j)_{1\leq j\leq N}$ such that centralization Pareto dominates autarky for any value of e. □

C. Proof of Proposition 4

We proceed by backward induction to find the optimum design of tax incentives for jurisdictions.

Actuarial insurance.
Jurisdictional program. The jurisdiction j's program is

$$\begin{aligned} &\forall j \in [\![1; N]\!],\ \max_{a_j} W_j^a = I - \Pi_j^a(a_j, a_{j-1}) - t_j, \\ &u.c.\ \ t_j \geq \tfrac{c}{2}a_j^2 + T_j - \tau_j^a a_j. \end{aligned} \quad (35)$$

That is

$$\forall j \in [\![1; N]\!],\ \max_{a_j} W_j^a = I - \Pi_j^a(a_j, a_{j-1}) - \frac{c}{2}a_j^2 - T_j + \tau_j^a a_j. \quad (36)$$

The first order condition leads to

$$\forall j \in [\![1; N]\!],\ a_j^{Ta} = \frac{L + \tau_j^a}{c}. \quad (37)$$

Government program. Knowing the jurisdictional reaction, central government maximizes the sum of all jurisdictions wealth.

$$\begin{array}{ll} \max\limits_{T_j^{a0},\tau_j^a} \sum\limits_{1\leq i\leq N} W_i^a = \sum\limits_{1\leq i\leq N} [I - \Pi_i^a(a_i^{Ta}, a_{i-1}^{Ta}) - \frac{c}{2}(a_i^{Ta})^2 - T_i + \tau_i^a a_i^{Ta}], \\ u.c. \sum\limits_{1\leq i\leq N} T_i - \tau_i^a a_i^{Ta} \geq 0. \end{array} \tag{38}$$

That is,

$$\begin{cases} \max\limits_{\tau_j^a} \sum\limits_{1\leq i\leq N} [I - \Pi_i^a(a_i^{Ta}, a_{i-1}^{Ta}) - \frac{c}{2}(a_i^{Ta})^2], \\ \sum\limits_{1\leq i\leq N} T_i \geq \sum\limits_{1\leq i\leq N} \tau_i^a a_i^{Ta}. \end{cases} \tag{39}$$

Thus,

$$\begin{cases} \forall j \in [\![1; N-1]\!],\ \tau_j^a = eL, \\ \forall j \in [\![1; N-1]\!],\ a_j^{Ta} = (1+e)\frac{L}{c}, \\ \tau_N^a = 0, \\ a_N^{Ta} = \frac{L}{c}, \\ \sum\limits_{1\leq i\leq N} T_i \geq e(N-1)(1+e)\frac{L^2}{c}. \end{cases} \tag{40}$$

The prevention levels reached in the centralized case are implemented. Externalities have been internalized.

Tax incentives Pareto dominate autarky if all jurisdictions are better off and the central budget constraint is verified. This leads to the following constraints system, with at least one of the N first inequalities strictly satisfied:

$$\begin{cases} W_1^{Ta*} - W_1^{a*} = \left[e + \dfrac{e^2}{2}\right]\dfrac{L^2}{c} - T_1 \geq 0 \qquad \text{for } j = 1, & (41) \\ W_j^{Ta*} - W_j^{a*} = \left[e + \dfrac{3e^2}{2}\right]\dfrac{L^2}{c} - T_j \geq 0 \qquad \forall j \in [\![2; N-1]\!], & (42) \\ W_N^{Ta*} - W_N^{a*} = e^2\dfrac{L^2}{c} - T_N \geq 0 \qquad \text{for } j = N, & (43) \\ \sum\limits_{1\leq j\leq N} T_j \geq e(N-1)(1+e)\dfrac{L^2}{c}. & (44) \end{cases}$$

This equation system is satisfied by $T_1 = e\frac{L^2}{c}; \forall j \in [\![2; N-1]\!],\ T_j = \left[e + e^2\right]\frac{L^2}{c}; T_N = e^2\frac{L^2}{c}$. Therefore there exists a system of transfers $(T_j)_{1\leq j\leq N}$ such that a set of tax incentives for jurisdictions Pareto dominates autarky for any value of $e \neq 0$. If $e = 0$, actuarial insurance in autarky leads to the optimum prevention measures. □

Uniform insurance.
Jurisdictional program. The jurisdiction's j program is

$$\begin{array}{l} \forall j \in [\![1; N]\!],\ \max\limits_{a_j} W_j^u = I - \Pi^u(a_1, ..., a_N) - t_j, \\ u.c.\ \ t_j \geq \frac{c}{2}a_j^2 + T_j - \tau_j^u a_j. \end{array} \tag{45}$$

That is

$$\forall j \in [\![1; N]\!],\ \max_{a_j} W_j^u = I - \Pi^u(a_1, ..., a_N) - \frac{c}{2}a_j^2 - T_j + \tau_j^u a_j. \tag{46}$$

We get

$$\forall j \in [\![1; N-1]\!],\ a_j^{Tu} = \frac{(1+e)}{N}\frac{L}{c} + \frac{\tau_j^u}{c}, \tag{47}$$

$$j = N,\ a_N^{Tu} = \frac{1}{N}\frac{L}{c} + \frac{\tau_N^u}{c}. \tag{48}$$

Government program. Central government maximizes the sum of all jurisdictions wealth.

$$\begin{aligned}&\max_{T_j^{u0},\tau_j^u} \sum_{1\leq i\leq N} W_i^u = \sum_{1\leq i\leq N} [I - \Pi^u(a_1^{Tu},...,a_N^{Tu}) - \tfrac{c}{2}(a_i^{Tu})^2 - T_i + \tau_i^u a_i^{Tu}],\\ &u.c. \sum_{1\leq i\leq N} T_i - \tau_i^u a_i^{Tu} \geq 0.\end{aligned} \tag{49}$$

That is,

$$\begin{cases}\max_{\tau_j^u} \sum_{1\leq i\leq N} [I - \Pi^u(a_1^{Tu},...,a_N^{Tu}) - \frac{c}{2}(a_i^{Tu})^2],\\ \sum_{1\leq i\leq N} T_i \geq \sum_{1\leq i\leq N} \tau_i^u a_i^{Tu}.\end{cases} \tag{50}$$

Thus,

$$\begin{cases}\forall j \in [\![1;N-1]\!],\ \tau_j^u = (N-1)\frac{1+e}{N}L,\\ \forall j \in [\![1;N-1]\!],\ a_j^{Tu} = (1+e)\frac{L}{c},\\ \tau_N^u = \frac{N-1}{N}L,\\ a_N^{Tu} = \frac{L}{c},\\ \sum_{1\leq j\leq N} T_j \geq \frac{N-1}{N}\Bigg[(N-1)(1+e)^2+1\Bigg]\frac{L^2}{c}.\end{cases} \tag{51}$$

The prevention levels reached in the centralized case are again implemented.

Tax incentives Pareto dominate autarky if all jurisdictions are better off and the central budget constraint is verified. This leads to the following constraints system, with at least one of the N first inequalities strictly satisfied:

$$\begin{cases}W_j^{Tu*} - W_j^{u*} = \dfrac{N-1}{N^2}\left[\dfrac{3}{2}(N-1)(1+e)^2+1\right]\dfrac{L^2}{c} - T_j \geq 0 \qquad \forall j \in [\![1;N-1]\!], & (52)\\ W_N^{Tu*} - W_N^{u*} = \dfrac{N-1}{N^2}\left[(N-1)(1+e)^2+\dfrac{N+1}{2}\right]\dfrac{L^2}{c} - T_N \geq 0 \qquad \text{for } j = N, & (53)\\ \displaystyle\sum_{1\leq j\leq N} T_j \geq \dfrac{N-1}{N}\left[(N-1)(1+e)^2+1\right]\dfrac{L^2}{c}. & (54)\end{cases}$$

This equations system is satisfied by $\forall j \in [\![1;N-1]\!],\ T_j = \frac{N-1}{N^2}\Bigg[(N-1)(1+e)^2+1\Bigg]\frac{L^2}{c}$; $T_N = \frac{N-1}{N^2}\Bigg[(N-1)(1+e)^2+\frac{N+1}{2}\Bigg]\frac{L^2}{c}$, as soon as $N \geq 2$. There exists so a system of transfers $(T_j)_{1\leq j\leq N}$ such that a set of tax incentives to jurisdictions Pareto dominates autarky for any value of e. □

D. Proof of Corollary 1

Actuarial insurance.
Jurisdictional program. The jurisdiction j's program is

$$\begin{aligned}&\forall j \in [\![1;N]\!],\ \max_{a_j} W_j^a = I - \Pi_j^a(a_j,a_{j-1}) + \gamma_a a_j - t_j,\\ &u.c.\ \ t_j \geq \tfrac{c}{2}a_j^2 + T_j.\end{aligned} \tag{55}$$

This leads to

$$\forall j \in [\![1;N]\!],\ a_j^{Ga} = \frac{L+\gamma^a}{c}. \tag{56}$$

Government program. The government program is:

$$\begin{aligned}&\max_{T_j,\gamma^a} \sum_{1\leq i\leq N} W_i^a = \sum_{1\leq i\leq N} I - \Pi_i^a(a_i^{Ga},a_{i-1}^{Ga}) + \gamma^a a_i^{Ga} - \tfrac{c}{2}(a_i^{Ga})^2 - T_i\\ &u.c. \sum_{1\leq i\leq N} T_i - \gamma^a a_i^{Ga} \geq 0.\end{aligned} \tag{57}$$

The first order condition of the government program is

$$\gamma^a = \frac{N-1}{N} eL. \tag{58}$$

Thus,

$$\forall j \in [\![1; N]\!],\ a_j^{Ga} = \left(1 + \frac{N-1}{N} e\right) \frac{L}{c}. \tag{59}$$

By definition of the program, social welfare is improved. However, the prevention levels obtained in the centralized case are not implemented.

Final wealth in the presence of transfers $(T_j)_{1 \le j \le N}$ is:

$$W_j^a = \begin{cases} I - p^0 L + \dfrac{1}{2}\left[1 + \dfrac{N-1}{N} e\right]^2 \dfrac{L^2}{c} - T_1 & \text{for } j = 1, \\ I - p^0 L + \dfrac{1}{2}\left[1 + \dfrac{N-1}{N} e\right]^2 \dfrac{L^2}{c} + e\left[1 + \dfrac{N-1}{N} e\right] \dfrac{L^2}{c} - T_j & \forall j \in [\![2; N]\!]. \end{cases}$$

The centralized case Pareto dominates autarky if all jurisdictions are better off and the central budget constraint is verified. This leads to the following constraints system, with at least one of the N first inequalities strictly satisfied:

$$\begin{cases} W_1^a - W_1^{a*} = \dfrac{N-1}{N} e\left[1 + \dfrac{N-1}{N}\dfrac{e}{2}\right] \dfrac{L^2}{c} - T_1 \ge 0 & \text{for } j = 1, & (60) \\ W_j^a - W_j^{a*} = \dfrac{N-1}{N} e\left[1 + e + \dfrac{N-1}{N}\dfrac{e}{2}\right] \dfrac{L^2}{c} - T_j \ge 0 & \forall j \in [\![2; N]\!], & (61) \\ \displaystyle\sum_{1 \le j \le N} T_j \ge (N-1)e\left(1 + \dfrac{N-1}{N} e\right) \dfrac{L^2}{c}. & & (62) \end{cases}$$

As $\frac{N-1}{N} e\left[N\left(1 + \frac{N-1}{N}\frac{e}{2}\right) + (N-1)e\right] \frac{L^2}{c} > (N-1)e\left(1 + \frac{N-1}{N} e\right) \frac{L^2}{c}$ is always verified if $e \neq 0$, there exists a system of transfers $(T_j)_{1 \le j \le N}$ such that premium modulation Pareto dominates autarky, for all $e \neq 0$. If $e = 0$, actuarial insurance in autarky leads to the optimum prevention measures.

Uniform insurance.
Jurisdictional program. Jurisdiction j's program leads to

$$a_j^{Gu} = \begin{cases} \dfrac{(1+e)}{N} \dfrac{L}{c} + \dfrac{\gamma^u}{c} & \forall j \in [\![1; N-1]\!], & (63) \\ \dfrac{1}{N} \dfrac{L}{c} + \dfrac{\gamma^u}{c} & \text{for } j = N. & (64) \end{cases}$$

Government program. The first order condition of the government program is

$$\gamma^u = \frac{N-1}{N^2} \Big[(1+e)(N-1) + 1\Big] L. \tag{65}$$

Thus,

$$a_j^{Gu} = \begin{cases} \left[(1+e) + \dfrac{N-1}{N}\Big((1+e)(N-1) + 1\Big)\right] \dfrac{L}{cN} & \forall j \in [\![1; N-1]\!], & (66) \\ \left[1 + \dfrac{N-1}{N}\Big((1+e)(N-1) + 1\Big)\right] \dfrac{L}{cN} & \text{for } j = N. & (67) \end{cases}$$

Here again, social welfare is improved compared to autarky.

Final wealth in the presence of transfers $(T_j)_{1\leq j\leq N}$ is:

$$W_j^u = \begin{cases} I - p^0L + \Big[\frac{3}{2}(1+2e+e^2) - \frac{1}{N}(1+5e+4e^2) + \frac{1}{N^2}(\frac{9}{2}e^2+2e) - \frac{1}{N^3}(e+3e^2) + \frac{e^2}{2N^4}\Big]\frac{L^2}{c} - T_j & \forall j \in [\![1; N-1]\!], \\ I - p^0L + \Big[\frac{3}{2}(1+2e+e^2) - \frac{1}{N}(1+5e+3e^2) + \frac{1}{N^2}(3e^2+5e) - \frac{1}{N^3}(e+3e^2) + \frac{e^2}{2N^4}\Big]\frac{L^2}{c} - T_N & \text{for } j = N. \end{cases}$$

The centralized case Pareto dominates autarky if all jurisdictions are better off and the central budget constraint is verified. This leads to the following constraints system, with at least one of the N first inequalities strictly satisfied:

$$\begin{cases} W_j^u - W_j^{u*} = \Big[\frac{3}{2}(1+2e+e^2) - \frac{1}{N}(2+7e+5e^2) + \frac{1}{N^2}(\frac{1}{2}+5e+6e^2) - \frac{1}{N^3}(e+3e^2) + \frac{e^2}{2N^4}\Big]\frac{L^2}{c} - T_j \geq 0 & \forall j \in [\![1; N-1]\!], \\ W_N^u - W_N^{u*} = \Big[\frac{3}{2}(1+2e+e^2) - \frac{1}{N}(2+7e+4e^2) + \frac{1}{N^2}(\frac{1}{2}+5e+6e^2) - \frac{1}{N^3}(e+3e^2) + \frac{e^2}{2N^4}\Big]\frac{L^2}{c} - T_N \geq 0 & \text{for } j = N. \\ \sum_{1\leq j\leq N} T_j \geq (N-1)\Big[\frac{(1+e)(N-1)+1}{N}\Big]^2\frac{L^2}{c}. \end{cases} \tag{68}$$

For high values of N, for all e, there exists a system of transfers $(T_j)_{1\leq j\leq N}$ such that premium modulation Pareto dominates autarky. □

E. Proof of Proposition 5

For notational simplicity, we denote $\Pi_D^u = \Pi_D^u(a_1, ..., a_N)$.
Each jurisdiction selects its level of prevention by maximizing its expected utility (see Equation 24). The first order condition obtained is

$$\forall j \in [\![1; N]\!],\ -u(W_j^L) + P_j(a_j, a_{j-1})u'(W_j^L)\Big[-\frac{\partial P^u}{\partial a_j}[L - D(a_j)] + (P^u - 1)\frac{\partial D}{\partial a_j} - ca_j\Big]$$
$$+u(W_j^{NL}) + (1 - P_j(a_j, a_{j-1}))u'(W_j^{NL})\Big[-\frac{\partial P^u}{\partial a_j}[L - D(a_j)] + P^u\frac{\partial D}{\partial a_j} - ca_j\Big] = 0. \tag{69}$$

This defines the optimum prevention level of jurisdiction j, which is a function of δ.

The first order condition for $\delta = 0$ leads to the condition corresponding to the optimum prevention levels under complete uniform insurance in autarky.

$$\forall j \in [\![1; N]\!],\ ca_j^{u*}(\delta = 0) = -\frac{\partial P^u}{\partial a_j}L. \tag{70}$$

We want to determine the sign of $(\frac{\partial a_j^{u*}}{\partial \delta})_{1\leq j\leq N}$. Thus, we differentiate the first order condition obtained above (see Equation 69) with respect to δ. This differentiation leads to the following equation for $\delta = 0$

$$\forall j \in [\![1; N]\!],\ c\frac{\partial a_j^{u*}}{\partial \delta}|_{\delta=0} = \Big(\frac{\partial P^u}{\partial a_j} - 1\Big)\frac{\partial D}{\partial \delta} + \Big[P^u - P_j\Big]\frac{\partial^2 D}{\partial \delta \partial a_j}. \tag{71}$$

This result holds for all forms of deductibles. We consider the following deductible: $D(a_j) = \delta(p^0 - a_j)$. So $\frac{\partial^2 D}{\partial \delta \partial a_j} = -1$. For the clarity of reading, we omit to denote $a_j^{u*}(\delta = 0)$ when necessary and keep instead the notation a_j^{u*}. We get

$$\forall j \in [\![1; N-1]\!],\ c\frac{\partial a_j^{u*}}{\partial \delta}|_{\delta=0} = \Big(1 - \frac{1+e}{N}\Big)(p^0 - a_j^{u*}) + (P_j - P^u), \tag{72}$$
$$j = N,\ c\frac{\partial a_N^{u*}}{\partial \delta}|_{\delta=0} = \Big(1 - \frac{1}{N}\Big)(p^0 - aN^{u*}) + (P_N - P^u). \tag{73}$$

Thus, we have for high values of N

$$j = 1,\ c\frac{\partial a_1^{u*}}{\partial \delta}|_{\delta=0} = (1-e)(p^0 - a_j^{u*}) - \frac{(p^0 - a_N^{u*})}{N} + \frac{N-1}{N}ep^0 > 0, \tag{74}$$
$$\forall j \in [\![2; N-1]\!],\ c\frac{\partial a_j^{u*}}{\partial \delta}|_{\delta=0} = (p^0 - a_j^{u*}) - \frac{(p^0 - a_N^{u*})}{N} - \frac{ep^0}{N} > 0, \tag{75}$$
$$j = N,\ c\frac{\partial a_N^{u*}}{\partial \delta}|_{\delta=0} = -\frac{N-1-e}{N}(p^0 - a_j^{u*}) + 2\frac{N-1}{N}(p^0 - a_N^{u*}) - \frac{ep^0}{N} > 0. \tag{76}$$

An increase of δ increases the prevention levels in all jurisdictions. We can compute the first derivative of the expected utility for jurisdiction j with respect to δ to explain the different terms.

$$\begin{aligned}\frac{\partial EU_j(a_j(\delta), a_{-j}(\delta), \delta)}{\partial \delta} &= \frac{\partial P_j}{\partial \delta} u(W_j^L) - \frac{\partial P_j}{\partial \delta} u(W_j^{NL}) \\ +P_j u'(W_j^L)\Big[&- \frac{\partial P^u}{\partial \delta}[L - D(a_j^{u*})] + (P^u - 1)(-\delta \frac{\partial a_j^{u*}}{\partial \delta} + p^0 - a_j^*) - c a_j^{u*} \frac{\partial a_j^{u*}}{\partial \delta}\Big] \\ +(1-P_j) u'(W_j^{NL})\Big[&- \frac{\partial P^u}{\partial \delta}[L - D(a_j^{u*})] + P^u(-\delta \frac{\partial a_j^{u*}}{\partial \delta} + p^0 - a_j^{u*}) - c a_j^{u*} \frac{\partial a_j^{u*}}{\partial \delta}\Big]. \end{aligned} \tag{77}$$

When $\delta = 0$, $W_j^L = W_j^{NL} = W_j$ and this becomes by using Equation 70

$$\begin{aligned}\frac{\partial EU_j(a_j(\delta), a_{-j}(\delta), \delta)}{\partial \delta}|_{\delta=0} &= u'(W_j)\Big[(P^u - P_j)(p^0 - a_j^{u*}) - c a_j^{u*} \frac{\partial a_j^{u*}}{\partial \delta} - \frac{\partial P^u}{\partial \delta} L\Big], \\ \text{with } \frac{\partial P^u}{\partial \delta} &= -\frac{1}{N}\Big[(1+e)\frac{\partial a_1^{u*}}{\partial \delta} + (N-2)(1+e)\frac{\partial a_j^{u*}}{\partial \delta} + \frac{\partial a_N^{u*}}{\partial \delta}\Big].\end{aligned}$$

For high values of N, this expression is equivalent to a positive expression:

$$\frac{\partial EU_j(a_j(\delta), a_{-j}(\delta), \delta)}{\partial \delta}|_{\delta=0} \sim (1+e)p^0 \frac{L}{c} > 0. \tag{78}$$

□