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Economic Resilience

Definition and Measurement

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Abstract

The welfare impact of a disaster does not only depend on the physical characteristics of the event or its direct impacts in terms of lost lives and assets. Welfare impacts also depend on the ability of the economy to cope, recover, and reconstruct and therefore to minimize aggregate consumption losses. This ability can be referred to as the macroeconomic resilience to natural disasters. Macroeconomic resilience has two components: instantaneous resilience, which is the ability to limit the magnitude of immediate production losses for a given amount of asset losses, and dynamic resilience, which is the ability to reconstruct and recover. Welfare impacts also depend on micro-economic resilience, which depends on the distribution of losses; on households' vulnerability, such as their pre-disaster income and ability to smooth shocks over time with savings, borrowing, and insurance, and on the social protection system, or the mechanisms for sharing risks across the population. The (economic) welfare disaster risk in a country can be reduced by reducing the exposure or vulnerability of people and assets (reducing asset losses), increasing macroeconomic resilience (reducing aggregate consumption losses for a given level of asset losses), or increasing microeconomic resilience (reducing welfare losses for a given level of aggregate consumption losses). The paper proposes rules of thumb to estimate macroeconomic and microeconomic resilience based on the relevant parameters in the economy. It also provides a toolbox of policies to increase macro- or micro-economic resilience and a list of indicators that can be used to build a resilience indicator.

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Economic Resilience: Definition and Measurement[1]

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1 Introduction

A natural disaster is not a "natural" event. Human and natural systems are affected by *natural hazards*, such as earthquakes, storms, hurricanes, intense precipitations and floods, droughts, landslides, heat waves, cold spells, and thunderstorms. If a hazard affects a human system – from one house to one region – and causes sufficiently large negative consequences to this system, the event can then be labelled as a natural *disaster*. But a disaster occurs only when there is the conjunction of a natural event – the hazard – and a human system, leading to negative consequences. As such, what we call a natural disaster is thus above all a social and human event (World Bank 2010).

The most immediate consequences of natural disasters are the fatalities and casualties. Between 1980 and 2011, disasters have caused 2,275,000 fatalities[2], almost half of them in low-income countries (vs. 5% in high-income countries). The first priority of disaster risk management is therefore to save lives, especially in developing countries where most of these losses occur. There is a large toolbox of measures to do so, from improved coastal dikes and the protection of coastal wetlands and coral reefs to more resistant buildings and infrastructure (World Bank, 2013a). A very cost effective way of avoiding disaster fatalities is through early warning systems coupled with evacuation schemes (Hallegatte, 2012; Subbiah et al., 2008).

In addition to human losses, natural disasters have economic consequences, which also affect welfare. From an economic perspective, a natural disaster can be defined as a natural event that causes a perturbation to the functioning of the economic system, with a significant negative impact on assets, production factors, output, employment, or consumption.[3] When it happens, the perturbation affects the economic system in a way that goes beyond the immediate loss of assets and the monetary expenditures to replace damaged property. Additional consequences include the loss of output and production, loss of income and livelihood, rationing in some sectors, and loss of employment and tax revenues. On top of human losses, these consequences need to be accounted for to assess the disaster impact on the population's welfare.

The ability of an economy or a society to minimize welfare losses for a disaster of a given magnitude is often referred to as its *resilience*. In the context of the post-2015 Millennium Development Goals, the Sustainable Development Goals, and the second phase of the Hyogo Framework for Action, many initiatives aim at defining and measuring country-level *resilience* through appropriate indicators (e.g., Rose, 2013). These resilience indicators can possibly be used to measure the progress achieved in improving resilience in a given country, or to compare countries with each other to help target resources where they are the most needed or the most efficient. However, the complexity of the

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[2] Data from the EM-DAT database, created and maintained by the Center for Research on the Epidemiology of Disasters (CRED) at the Catholic University of Louvain.

[3] There are multiple formal definitions. The Center for Research on the Epidemiology of Disasters (CRED) at the Catholic University of Louvain defines a disaster as a natural situation or event which overwhelms local capacity and/or necessitates a request for external assistance. For a disaster to be listed in the EM-DAT database, at least one of the following criteria should be met: (i) 10 or more people are reported killed; (ii) 100 people are reported affected; (iii) a state of emergency is declared; (iv) a call for international assistance is issued.

mechanisms at stake and the high heterogeneity of countries, households, and disasters make the definition of a resilience indicator extremely difficult, and its measurement even more.

In this paper, I propose a definition of *economic resilience*, leaving aside many important non-economic dimensions of resilience (e.g., direct health and human impacts). This definition may be a good starting point to create an indicator for economic resilience that is meaningful and measurable. Doing so requires making difficult trade-offs between precision and accuracy on the one hand and simplicity and transparency on the other hand. As the reader will soon realize, some harsh simplifications are made in the paper for the sake of simplicity and applicability in a world of limited data.

The paper structure is presented in Figure 1. It starts by defining and discussing the aggregate economic cost of natural disasters. It summarizes the most important mechanisms that determine this cost, and highlights the fact that asset losses, i.e. the value of what has been damaged or destroyed by the disaster, is not a sufficient indicator of disaster welfare impacts. Estimating output, income, and consumption losses is also crucial.

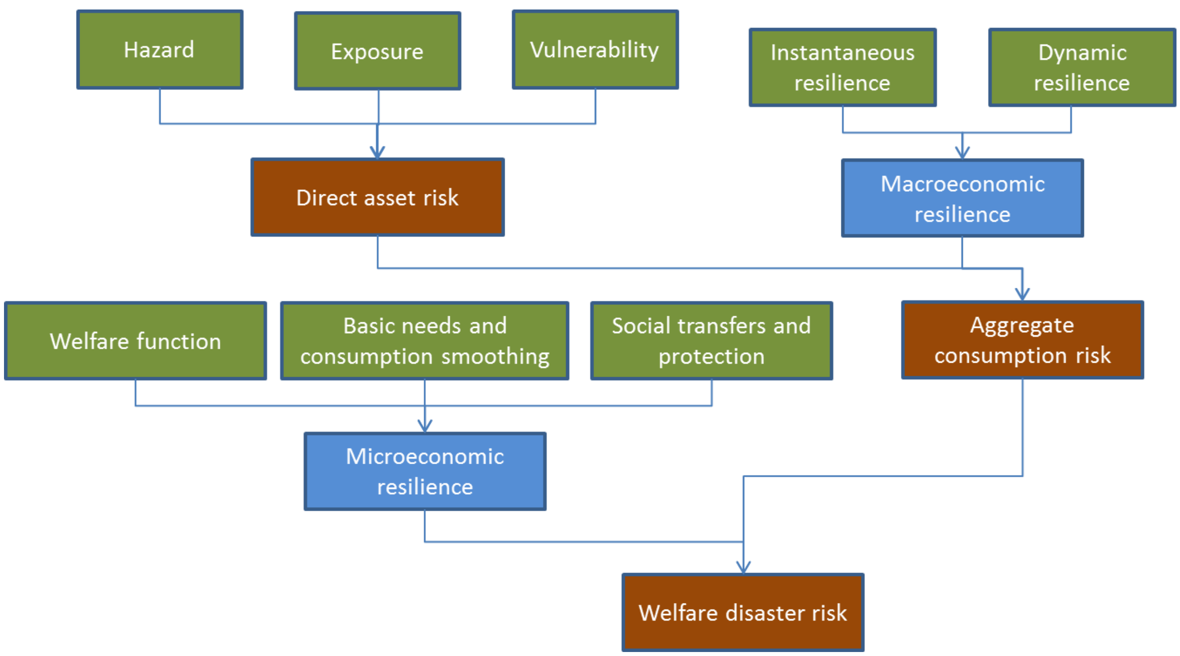

Figure 1: Structure of the assessment of welfare disaster risk. Here, welfare disaster risk only encompasses economic effects, leaving aside many other important considerations such as direct health impacts (see a discussion in the conclusion section). Green boxes represent characteristics of the economy; blue boxes represent the different resilience indicators; and brown boxes the various measures of disaster risk.

The paper discusses the methodologies and the models that are able to measure output losses and proposes a simple rule of thumb to take them into account when time and resources do not allow for a full modelling exercise. This rule makes it possible to define the *macroeconomic resilience* of the economic system as a combination of (1) *instantaneous resilience*, i.e. the ability to limit the magnitude of the immediate loss of income for a given amount of capital losses; and (2) *dynamic resilience*, i.e. the ability to reconstruct and recover quickly.

Then, the paper proposes a simple framework to assess the *microeconomic resilience* of households, that depends on the distribution of direct losses across households, the existence of basic needs, the ability to smooth the shock across time through savings, borrowing, insurance, and the ability to share risks across households through social protection.

By combining the micro- and macro-aspects, one can define and measure the *economic resilience* of a country and region and finally assess the (economic) *welfare disaster risk* by adding the combination of *hazard, exposure* and *vulnerability* into the analysis (i.e. direct asset risk). The structure of an assessment of the welfare disaster risk is proposed in Figure 1. As a conclusion, the paper suggests proxies and indicators to assess economic resilience indicators, a first step toward the construction of a meaningful and measurable indicator for economic resilience (see Table 2 at the end of this paper).

2 Macroeconomic resilience and the cost of a disaster[4]

2.1 Defining the economic cost

Many authors have discussed typologies of disaster impacts (e.g., Cochrane, 2004; Lindell and Prater, 2003; Pelling et al., 2002; Rose, 2004). These typologies usually distinguish between direct and indirect losses. Direct losses are the immediate consequences of the disaster physical phenomenon: the consequence of high winds, of water inundation, or of ground shaking. Typical examples include roofs that are destroyed by high winds, cars destroyed and roads washed away by floods, and injuries and fatalities from collapsed buildings. Direct losses are often classified into direct market losses (for goods that can be bought on a market, such as cars and buildings) and direct non-market losses (for what cannot be bought on a market, like human lives and ecosystems). Indirect losses (also labelled "higher-order losses" in Rose, 2004) include all losses that are not provoked by the disaster itself, but by its consequences; they span over a longer period of time than the event, and they affect a larger spatial scale or different economic sectors. They include some additional losses to assets (e.g., when an earthquake causes a fire or a toxic spill that damages assets) and effects on flows (e.g., through macroeconomic effects).

Here, instead of the direct/indirect typology, we use an alternative (and complementary) terminology. Like in (NRC, 2013, 2011; Rose et al., 2007b), we distinguish between *asset losses* (i.e., the *stock* of assets that is reduced), and *output losses* (i.e., a reduction in an income *flow*). Output losses include different categories that often overlap:

- *Business interruptions* (the interruption in production during the event);

[4] Section 2 of this paper is a summary with minor changes of the background paper "The Indirect Cost of Natural Disasters and an Economic Definition of Macroeconomic Resilience", prepared for and funded by the "Sovereign DRFI impact appraisal project", funded by UKaid, The World Bank, the Disaster Risk Financing and Insurance Program, and the Global Facility for Disaster Reduction and Recovery (GFDRR), and available here: https://www.gfdrr.org/DRFI1TM.

- *Production losses directly due to asset losses* (because damaged or destroyed assets cannot produce, during a period that is much longer than the event itself);
- *Supply-chain disruptions* (when lack of input or reduced demand is responsible for a reduction in production from a production site that is not directly affected);
- *Macro-economic feedbacks* (e.g., the impact of reduced final demand because consumers and businesses suffer from a reduced income, and the effect of lost tax revenue on public demand);
- *Long-term adverse consequences on economic growth* (e.g., due to changes in risk perception (including over-reactions) that can drive investors and entrepreneurs out of the affected area);
- *Increased production from the "reconstruction boom"* that acts as a stimulus for the economy.

Note that these output losses include household production, not only production by the productive and commercial sectors. For instance, the reduction in housing service (a service produced by houses and dwellings) is considered as an output loss, as are all services from other household assets (e.g., appliances).

Some of these impacts can be captured using classical economic indicators, such as Gross Domestic Product (GDP). There are however several issues when using GDP change as an indicator for output losses. A first question deals with the spatial scale: for large countries, the scale of the event and the scale of GDP measurement are very different, and a large shock for local populations can hardly be visible on national GDP. It does not mean, however, that welfare impacts are negligible. Second, GDP does not include non-market production and household production and therefore cannot capture a significant share of output losses. With a broader definition of output, it is possible to include at least some non-market and non-commercial impacts. Third, GDP is known to be a poor proxy for welfare because it does not capture wealth (e.g., stocks of assets) and does not account for inequality and distributional effects (Fleurbaey, 2009).

2.2 From asset losses to output losses

Damages to assets make them unable to produce: a damaged factory cannot build cars, a damaged road cannot be used, and a damaged house cannot be inhabited. The first step in an assessment of output losses is to estimate how much output is lost because of these direct asset losses. An obvious illustration of why these output losses are important is the difference between disaster scenarios with various reconstruction paces. In terms of welfare, there is a large difference between, on the one hand, a scenario in which all direct losses can be repaired in a few months thanks to an efficient reconstruction process and, on the other hand, a scenario in which reconstruction is inefficient and takes years.

2.2.1 Idealized framework

Economic theory states that, at the economic equilibrium and under certain conditions, the value of an asset is the net present value of its expected future production. In this case, the annual loss of output is equal to the value of the lost capital multiplied by the marginal productivity of capital (which is equal to the interest rate, increased by the depreciation rate). Assuming this equality is always verified, the output loss caused by capital loss is simply equal to the value of the lost asset, and summing the two is a double count.

Figure 2 illustrates this point in a scenario in which no reconstruction takes place: in that case, the production that is lost because of the disaster is equal to the value of the lost assets. In estimates of disaster consequences, what is referred to as "asset loss" is the replacement value of the capital. To have the equality of asset loss and output loss, a double equality needs to be verified: replacement value has to be equal to market value; and market value has to be equal to the net present value of expected output.

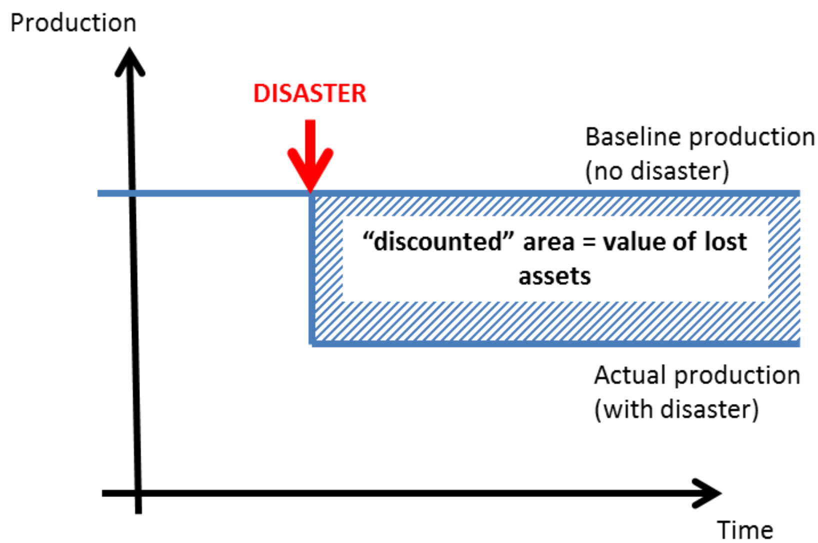

Figure 2. Production as a function of time, without disaster or in a scenario with disaster and no reconstruction. In a theoretical context, the discounted value of the lost production (from the disaster to the infinity) is equal to the value of lost assets.

In a theoretical and optimal economy at equilibrium, these two equalities are valid. First, if the market value of an asset is lower (higher) than the net value of its output, then investors will buy (sell) more of this asset to capture the difference in value, making asset price increase (resp. decrease). Second, if market value were higher (lower) than replacement value, then investors would increase (resp. decrease) the amount of physical capital to restore the equality between market and replacement value (assuming decreasing returns).

In such an idealized context, classical production functions can relate the inputs and the outputs in the production process. Often, the production function takes as inputs the amount of labor used in the production process (referred to as L) and the amount of capital (i.e., the value of all equipment used in the process, referred to as K), and gives the value of the production (expressed as Y):

$$Y = f(L, K) \quad (1)$$

In this framework, natural disasters can be modelled assuming they reduce instantaneously the stock of productive capital ($K_0 \rightarrow K_0 - \Delta K$), where ΔK is the value of asset losses.

Figure 3 illustrates this way of assessing the impact on output. The figure represents the production Y as a function of capital K. The production function is the blue line linking the origin of the graph to the point A. It is assumed that the pre-disaster situation is the point A, with capital K_0 and production Y_0.

For small shocks, the impact on production can be estimated using the marginal productivity of capital, i.e. the interest rate (or the marginal productivity of capital, taking into account the depreciation rate). This case is shown in Figure 3 as the point B. Point B is estimated using the orange dashed line, which is the tangent to the production function at point A; its slope is the marginal productivity of capital (i.e., how much more production is produced from one more unit of capital). The production level Y_1 is given by the orange line at the X-coordinate $K_0 - \Delta K$, and is the estimated residual production if the output loss is estimated by multiplying the value of the lost capital ΔK by the marginal productivity of capital r:

$$\Delta Y(t_0) = r\Delta K \qquad (2)$$

This relationship is equivalent to assuming that the net present value of output losses is equal to the value of lost assets.

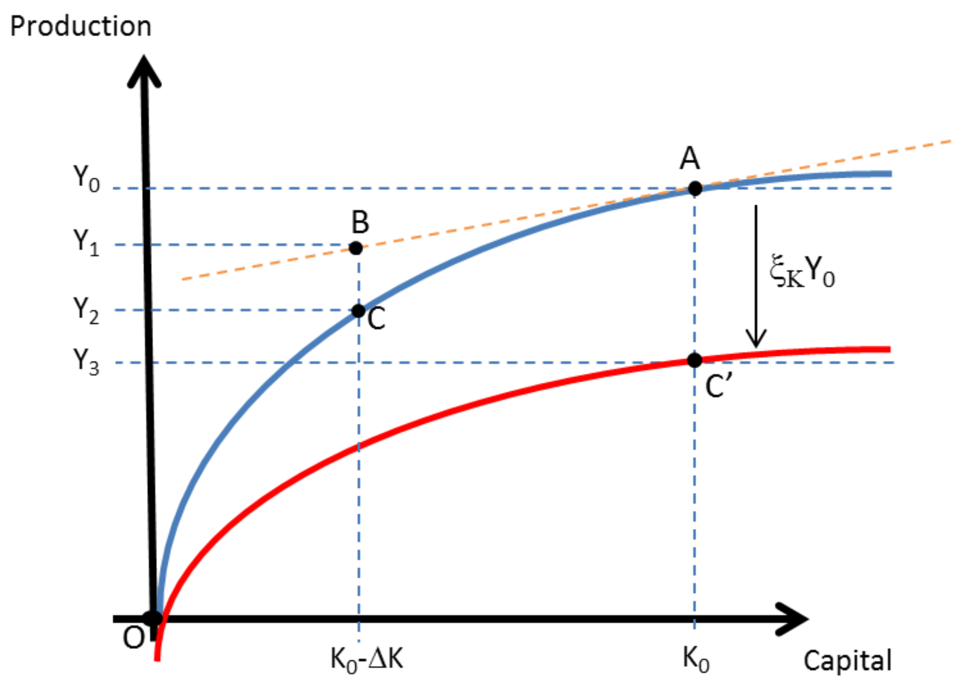

Figure 3. Production with respect to productive capital for different modelling assumptions.

In a more realistic setting, however, this method to assess output losses may lead to significant underestimation. The following subsections introduce several modifications to this framework to better represent the impacts of disasters.

2.2.2 Non-marginal shocks

The equality of asset value and output is valid only for marginal changes, i.e. for small shocks that do not affect the structure of the economy and the relative prices of different goods and services. The impact is different for large shocks. Most assets have “decreasing returns”, i.e. their productivity decreases with the total amount of asset. For instance, if there are one million cars in a city, the loss of one car is a marginal shock, and the output of this car should be equal (at the optimum) to the production cost of a car. But in practice, some cars have a larger productivity than others: some cars are driven 1000 km per year while others are driven 80,000 km per year; clearly the latter car is more productive than the former. In economic theory, the least productive car – i.e. the one that is driven the shortest distance per year – has an output equal to the production cost of cars. All the other ones have a higher productivity. As a result, the destruction of one car – assuming the least productive one is destroyed, see Section 2.2.3 – leads to an output loss equal to the replacement cost of the car. But the destruction of many cars will affect cars with increasing productivity levels, and leads to an output loss that is larger than the replacement value of these cars.

Such non-marginal shocks affect prices, while asset and output losses are often estimated assuming unchanged (pre-disaster) prices (e.g., assuming that if a house is destroyed, the family who owns the house can rent another house at the pre-disaster price). But this assumption is unrealistic if the disaster causes more than a small shock. In post-disaster situations, indeed, a significant fraction of houses may be destroyed, leading to changes in the relative price structure. In this case, the price of alternative housing can be much higher than the pre-disaster price, as a consequence of the disaster-related scarcity in the housing market.[5] For large shocks, estimating the value of lost housing service should take into account the price change. Compared with an assessment based on the pre-disaster prices, it can lead to a significant increase in the assessed disaster cost. The same reasoning is possible in all other sectors, including transportation, energy, water, and health. In extreme cases, there may be rationing, i.e. the price cannot clear the market and supply is not equal to demand. This is because markets are not at equilibrium in disaster aftermath. The “If I can pay it, I can get it” assumption is not always valid in post-disaster situations (e.g., there is no available house for rent at any price, there is no qualified worker to repair a roof). In these situations, even using the post-disaster price underestimates the losses. Appendix A provides details on this issue.

To account for these effects of non-marginal shocks on the capital stock (or for the destruction of non-marginal capital), one can use the full production function, and decreasing the amount of capital from K_0 to $K_0 - \Delta K$. This is what is shown by the point C in Figure 3. The point C gives the value of production Y_2 given by the production function, i.e. $Y_2 = f(L, K - \Delta K)$. In that case, output losses are larger than in the idealized (marginal) framework and Equation (2) is replaced by:

$$\Delta Y = f(L, K) - f(L, K - \Delta K) \quad (3)$$

[5] Conversely, if a disaster makes a large fraction of the population leave the city (such as Katrina in New Orleans) or if many jobs disappear as a result, then the cost of housing may decrease because of the shock. Changes in risk perceptions could also lead to a decrease in home values, as illustrated in (Bin and Polasky, 2004).

2.2.3 Impact on the "non-marginal" capital

Equation (3) assumes that the destructions from the disaster affect only the least productive assets, or that capital consists only in one-commodity, perfectly substitutable. In the previous example with destroyed cars, it is assumed that if one car is destroyed, then it is the least productive (i.e. the one that is driven the shortest distance per year). Or equivalently, it is assumed that the owner of the destroyed car will instantaneously buy the least productive car to its owner (which makes sense because the former makes a more efficient use of the car than the latter, but is unrealistic given the involved transaction costs, especially in disaster aftermaths).

This limits links to the Cambridge capital theory controversy, and the limits of the one-commodity model (Cohen and Harcourt, 2003). In particular, it is connected to Robinson's (1974) critics "history vs. equilibrium" and the problem of path dependency. Indeed, the production given by a production function is assumed to be the result of a process of (optimal) capital accumulation. Only the assumption of optimal capital accumulation allows to remove relative prices and interest rate from the valuation of the capital stock and make it possible to measure capital with only one variable K (Cohen, 1989).

When one calculates $Y_2 = f(L, K - \Delta K)$, one represents a process of capital accumulation followed by the destruction of a random fraction of this capital, not a continuous process of capital accumulation. It is very unlikely that the situation characterized by an optimal accumulation of capital until $(K - \Delta K)$ is equivalent to a situation characterized by an optimal accumulation of capital until K and the destruction of an amount ΔK of capital. And it is very unlikely that these two situations correspond to the same level of production. Path dependency issues make the use of a classical production function inappropriate.

To account for the fact that disasters affect capital in a way that is different from optimal accumulation (or de-accumulation) of capital, Hallegatte et al. (2007) propose to modify the Cobb–Douglas production function by introducing a term ξ_K, which is the *proportion of non-destroyed capital*. This new variable ξ_K is such that the effective capital is $K=\xi_K \cdot K_0$, where K_0 is the potential productive capital, in absence of disaster. In Figure 3, the new production level is given by the relationship:

$$Y_3 = \xi_K\, f(L,K_0) = A\, \xi_K\, L^{\lambda}\, K_0^{\mu} \qquad (4)$$

With this new production function, an x% destruction of the productive capital reduces production by x%, and the loss in output is approximately equal to $1/\mu$ times the loss of asset estimated using the normal production function, where μ is the parameter that describes decreasing returns in the production function. In Figure 3, the new production function is the red line and the new production Y_3 is given by the point C'.

With these assumptions, the loss in output is not equal to the value of lost assets multiplied by the marginal productivity of capital anymore. Instead, output losses are equal to the value of lost assets multiplied by the average productivity of capital, which is $1/\mu$ times larger than the marginal capital productivity. With classical values for μ, it means that output reduction at the time of shock (t_0) is about

3 times larger than what is suggested by the market value of damaged assets (i.e. what is estimated with Eq.(2)). As result, production losses are then given by:

$$\Delta Y(t_0) = \frac{1}{\mu} r \Delta K \qquad (5)$$

2.2.4 Externalities and distortions

For the replacement value and the market value to be equal, the economy needs to be at its economic optimum, i.e. the amount of capital is such that its return is equal to the (unique) interest rate. This is not always the case especially in sectors affected by disasters. In some sectors, expectations can be heavily biased (e.g., in the housing market) and markets distorted, leading to large differences between capital returns and the interest rate. This is also unlikely for infrastructure and public assets. Since these assets are not exchanged on markets, they have no market prices. Moreover, they are not financed by decisions of private investors using financial returns, but by government decisions through a political process taking into account multiple criteria (e.g., land-use planning objectives). Furthermore, output losses need to be estimated from a social point-of-view. The equality between market value (for the owner) and expected output (for society) is valid only in absence of externalities. Some assets that are destroyed by disasters may exhibit positive externality. It means that their value to society is larger than the value of the owner’s expected output. Public goods have this characteristic, among which include infrastructure projects, health services, and education services.[6]

An example is provided by the San Francisco Oakland Bay Bridge, which is essential to economic activity in San Francisco and had to be closed for one month after the Loma Prieta earthquake in 1989. Its replacement value has no reason to be equal to the loss in activity caused by the bridge closure, because the bridge production is not sold on a market, the bridge has no market value, and the social return on capital of the bridge is likely to be much higher than the interest rate. Another example is the health care system in New Orleans. Beyond the immediate economic value of the service it provided, a functioning health care is necessary for a region to attract workers (in other terms, it creates a positive externality). After Katrina’s landfall on the city in 2005, the lack of health care services made it more difficult to attract construction workers to the region, and thus slowed down the reconstruction; as a result, the cost for the region of the loss in health care services was larger than the direct value of this service.

To account for these effects, the value of lost assets (ΔK) should be evaluated taking into account externalities and existing distortions, not from replacement costs only. In practice, doing so is difficult however. Assuming that assets lost to disasters exhibit mostly positive externalities, this effect provides one additional reason to use a capital productivity that is higher than the marginal productivity (as in Eq.(5), which uses the average productivity).

[6] Other assets may exhibit negative externality, e.g. air pollution from coal power plant.

2.2.5 "Ripple effects", non-affected capital, and supply chains

Output losses are not only due to forgone production from the assets that have been destroyed or damaged by the event. Assets that have not been affected by the hazards can also reveal unable to produce at the pre-event level because of indirect impacts, sometimes referred to as "ripple effects".

Ripple-effect and diffusion of the shock in the economic system

(McCarty and Smith, 2005) investigated the impact of the 2004 hurricane season on households in Florida, and find that among the 21% of the households who were forced to move after the disaster, 50% had to do so because of the loss of utilities (e.g., they had no running water). Only 37% of them had to move because of structural damages to the house. (Tierney, 1997) and (Gordon et al., 1998) investigate the impact of the Northridge earthquake in 1994 in Los Angeles; they find also that loss of utility services and transport played a key role. Tierney surveys the reasons why small businesses had to close after the earthquake. The first reason, invoked by 65% of the respondents (several answers were possible), is the need for clean-up. After that, the five most important reasons are loss of electricity, employees unable to get to work, loss of telephones, damages to owner's or manager's home, and few or no customers, with percentages ranging from 59% to 40%. These reasons are not related to structural damages to the business itself, but to offsite impacts. (Gordon et al., 1998) ask businesses to assess the earthquake loss due to transportation perturbations, and find that this loss amounts to 39% of total losses. (Kroll et al., 1991) find comparable results for the Loma Prieta earthquake in San Francisco in 1989: the major problems for small business were customer access, employee access, and shipping delays, not structural damages. Utilities (electricity, communication, etc.) caused problems, but only over the short term, since these services were restored rapidly; only transportation issues led to long lasting consequences. (Rose and Wei, 2013) investigate the impact of a 90-day disruption at the twin seaports of Beaumont and Port Arthur, Texas, and find that – even in the absence of other losses – regional gross output could decline by as much as $13 billion at the port region level (and that specific actions to cope with the shock can reduce these impacts by nearly 70%).

Output losses are also due to complex interactions between businesses. Business perturbations may indeed also arise from production bottlenecks through supply-chains of suppliers and producers.[7] These ripple-effects can be "backward" or "forward":

- *Backward ripple-effects* arise when the impact propagates from clients to suppliers, i.e. when a business cannot produce, and thus reduces its demand to its suppliers, reducing their own activity (even in absence of direct damages).
- *Forward ripple-effects* arise when the impact propagates from suppliers to clients, i.e. when a business cannot produce and thus cannot provide its clients with inputs needed for their own production.

The output losses due to a disaster depend on the characteristics of the firm-to-firm networks, such as the average number of suppliers that firms have, or the shape and structure of the connection between

[7] These ripple effects can even take place within a factory, if one segment of the production process is impossible and therefore interrupts the entire production.

firms (Henriet et al., 2012). These results suggest that modern economies, with global supply chains, limited number of suppliers and small stocks, may be more vulnerable to natural disasters than traditional, close economies. However, detailed information on real-world economic networks is not available, and the available models remain overly simplistic. The impact of disasters on supply chains are tragically illustrated by the recent Tohoku-Pacific earthquake in Japan in March 2011, and its wide consequences on industrial production and exports, especially in the auto industry. As an example, The Economic Times, an Indian newspaper, reported that *"Japan's Toyota Motor will cut production at its Indian subsidiary by up to 70% between April 25 and June 4 due to disruption of supplies."*

In theoretical terms, these ripple-effects across sectors can be represented by the fact that capital is non-homogeneous: capital components are not perfectly substitutable within a network of economic activities, and the relative price of different types of capital depends on the relative quantity (again, this is the argument from (Robinson, 1974; Sraffa, 1960). If the stock of capital consists of an ensemble of capital categories that have some complementarity, then the destruction of one component may reduce the productivity of other components and thus have an impact that is larger than what could be expected from the analysis of one component only. One extreme example is the case of a road that is built out of a series of segments between point A and B: if one segment is destroyed, then the road is not usable and the other segments become useless. The output loss due to the destruction of one segment cannot be estimated based on the value of one segment, but requires an analysis of the entire system (the road). The same is true – at various degrees – of the entire economic system: the loss of one component can affect the other component and lead to losses that are higher (or lower) than the value of the asset loss suggests depending on the substitutability. This problem is removed if one assumes that the capital stock is the result of an optimal process of capital accumulation, but this assumption is not valid in post-disaster contexts.

This problem can be illustrated by replacing the classical production function f(L,K) by a function with two types of capital f(L,K_1,K_2). If there are decreasing returns in K_1 and K_2, the impact of a given loss $\Delta K=\Delta K_1+\Delta K_2$ depends on how losses are distributed across the two capitals. The loss in output is larger if all losses affect only one type of capital, compared with a scenario where the two capitals are equally affected. Because the relative prices of K_1 and K_2 depend of their quantity, it is impossible to define a total stock of capital as $K=K_1+K_2$, and the one-commodity production function is not applicable (Cohen, 1989).

Appendix A illustrates these effects in the extreme case where the production function has no substitution (a Leontief production function). In that case, the destruction by a disaster of a (marginal) amount ΔK_i of one type of capital would lead to a loss of output equal to:

$$\Delta Y(t_0) = \left(\frac{\sum \alpha_j}{\sum \alpha_j - \alpha_i}\right) r \Delta K_i \quad (6)$$

Where the $\{\alpha_i\}$ are parameters of the production function and describe the share of each type of capital in the total stock of capital. If α_i is very small – i.e. if one capital is very small in value but still essential in the production process – then the impact of a minimal asset loss can be very large. Typically, it is the case that if all electricity generation is impossible, most other production processes are interrupted.. Even though electricity generation represents a small share of GDP, the impact of such an event of total output can be very large (Rose et al., 2007a). As shown in many studies (e.g., Rose and Wei, 2013), however, there is always some substitutability among capital types, and the assumptions used in Eq. (6) is an extreme case.

Non-affected capital, idle capacity, and rescheduling

When capital cannot produce because of a lack of input (e.g., electricity, water), several options are available: input substitution, production rescheduling, mobilization of existing idle resources, and longer work hours when services are restored and can compensate for a significant fraction of the losses (Rose et al., 2007a). Loss of output in the affected area and during the disaster aftermath could also be compensated by increased production outside the affected area (e.g., when another region captures the market share lost by the affected region). Even within the affected area, output losses from destroyed capital can be compensated by increased production from factories and production units that did not suffer from losses and had idle capacity before the event (which depends on the pre-existing situation, see below).

In developing countries, where capital is scarce and (unskilled) labor abundant, large idle capacity do not exist in many sectors (e.g., electricity generation capacity is often lower than what demand would require). However, many developing country economies are plagued with large distortions that sometimes lead to excess investments in capital. In that latter case, it is possible that idle capacity is available and that the reduction in capacity due to a disaster has no impact.

These mechanisms can mitigate output losses, and can especially reduce the crowding-out effects of reconstruction on normal consumption and investment. But their ability to do so is limited, especially when losses are large. In case of large disasters, output losses will be largely dependent on two characteristics of the economy: the adaptability and flexibility of its production processes; and its ability to channel economic production toward its most efficient uses (Hallegatte, 2014).

Stimulus effects

Disasters lead to a reduction of production capacity, but also to an increase in the demand for the reconstruction sector and goods. Thus, the reconstruction acts in theory as a stimulus. For instance, (Albala-Bertrand, 2013) assumes that reconstruction spending has a Keynesian multiplier equal to two (each dollar spent in reconstruction increase GDP by two dollars). However, as any stimulus, its consequences depend on the pre-existing economic situation, such as the phase of the business cycle and the existence of distortions that lead to under-utilization of production capacities (Hallegatte and Ghil, 2008). If the economy is efficient and in a phase of high growth, in which all resources are fully used, the net effect of a stimulus on the economy will be negative, for instance through diverted resources, production capacity scarcity, and accelerated inflation. If the pre-disaster economy is depressed, on the other hand, the stimulus effect can yield benefits to the economy by mobilizing idle capacities. For instance, the 1999 earthquake in Turkey caused direct destructions amounting to 1.5 to 3% of Turkey's GDP, but consequences on growth remained limited, probably because the economy had significant unused resources at that time (the Turkish GDP contracted by 7% in the year preceding the earthquake). In this case, therefore, the earthquake may have acted as a stimulus and increased economic activity in spite of its human consequences. In 1992, when Hurricane Andrew made landfall on south Florida, the economy was depressed and only 50% of the construction workers were employed (West and Lenze, 1994). Reconstruction had a stimulus effect on the construction sector, which would have been impossible in a better economic situation (e.g., in 2004 when four hurricanes hit Florida during a housing construction boom).

Here, the stimulus benefits are not considered as a positive outcome of disasters. Indeed, the same stimulus benefits could be captured in the absence of a disaster, through a standard stimulus policy, and without the negative welfare and human impacts that come with disasters. For instance, output may be stimulated by the reconstruction of many houses destroyed by a hurricane; but the same output generation is possible by building new and better housing for the poor or by retrofitting existing buildings to make them more energy efficient, without the need for any destruction. The possibility of a stimulus effect would only reflect the fact that pre-existing economic policy is inappropriate, and this could be corrected independently of a disaster.

A simple representation

As a result of externalities and distortions, ripple-effects, and the mobilization of idle capacity, the loss of output estimated in Eq. (5) is magnified (or reduced) by a factor ($1+\alpha$). The reduction in output just after the shock is thus:

$$\Delta Y(t_0) = \frac{1+\alpha}{\mu} r \Delta K \qquad (7)$$

The parameter α represents the reduced (or increased) production of the capital that is not directly affected by the event, and depends on the ability of the economic system to (1) mobilize existing idle capacity (which depends on the existence of idle capacity); (2) adjust production networks to compensate for damaged production units (e.g., producers find new suppliers and clients rapidly), (3) channel remaining production toward its most productive uses (including reconstruction needs), and (4) increase imports to compensate for unavailable supplies. It is likely to be negative for relatively small disasters, and to become positive and then increase for larger-scale events. It is lower (and possibly negative) if there is a larger under-utilization of production capacity and idle capacity that can be mobilized.

This parameter also depends on other – more micro – considerations regarding the ability of firms to cope with shocks (see a framework to define firm resilience in Rose and Krausmann, 2013).[8] As such, the parameter α is linked to the concept of *"static resilience*" proposed by (Rose, 2013, 2009). He defines it as follows: *"Static resilience refers to the ability of an entity or system to maintain function when*

[8] Note that these ripple-effects can be particularly large when critical infrastructure (e.g., electricity networks) is affected. An extreme case is when terrorist attacks target critical infrastructure, see (Rose et al., 2007a); in this case, α can be extremely high, much higher than for natural disasters.

shocked. This is related in turn to a fundamental economic problem—how to efficiently allocate the resources remaining after the disaster. It is static because it can be attained by various means, such as conservation, input substitution, relocation, etc., that increase capacity to produce in subsequent time periods."

There are two reasons why ripple effects (and thus α and output losses $\Delta Y(t_0)$) are likely to increase non-linearly with the size of the disaster (and the amount of destruction). First, all economies have idle capacities (e.g., factories that do not produce as much as they technically can, and workers who could and sometime wish to work more hours). If lost production by affected capital is small enough to be fully compensated by increased production from non-affected idle capacity, then there is no output loss (Albala-Bertrand, 2013; Rose and Krausmann, 2013; Rose et al., 2007a). As a result, output losses appear only if direct losses are larger than a given threshold that depends on the pre-existing economic situation. Second, the "ripple effects" from infrastructure to firms and households and across firms are also likely to increase with the number of affected firms (and the individual loss of output).

In the absence of more information, it is possible to assume that α=0, keeping in mind that we are disregarding some potentially important effects. In very specific cases, different values could be used, for instance a -20% value if the shock occurs during a recession with large idle resources (e.g., the landfall of hurricane Andrew in Florida in 1992), or +20% if the transport sector is heavily affected, creating large-scale supply-chain issues (or in case of power generation issues such as in Japan after the 2011 earthquake and tsunami).

2.3 Reconstruction dynamics and total output losses

To assess the total output losses (integrated over time), one needs to make an assumption on the reconstruction dynamics. The amount of damages can be a misleading indicator of the reconstruction duration. The 10 billion Euros of reconstruction expenditures after the 2002 floods in Germany are relatively small compared with the country-level investment capacity: they correspond to only 10 days of total German investments. But reconstruction has been spread out over more than 3 years, suggesting that only a small fraction of investments can be dedicated to reconstruction (even though the return on investment from reconstruction should theoretically be higher than other investments, as suggested in Section 2.2), because of financial and technical constraints. Indeed, the reconstruction capacity is always limited by such constraints and it makes rebuilding after a large scale disaster much longer than after a small one (Benson and Clay, 2004). In other terms, the duration of the shock increases with its magnitude. As a result, the output losses – that depend on the magnitude of the shock and its duration – will increase more than proportionally with direct losses.

2.3.1 Modeling results

Many different models have been used to assess post-disaster output losses, and the most common are Input-Output (IO) or Calculable General Equilibrium (CGE) models. In these models, the economy is described as an ensemble of economic sectors, which interact through intermediate consumptions. These models however describe differently how these different sectors interact with each other, and how they react to shocks. Some models are based on the Input-Output (IO) linear assumption (Leontief, 1951), in which the production of one unit in one sector requires a fixed amount of inputs from other sectors, and in which prices do not play any role (Bockarjova et al., 2004; Haimes and Jiang, 2001; Hallegatte, 2014, 2008; Okuyama, 2004; Okuyama et al., 2004; Santos and Haimes, 2004). Other models are based on the Calculable General Equilibrium (CGE) framework, which assumes that changes in relative prices balance supply and demand in each sector (Rose and Liao, 2005; Rose et al., 2007a). A comprehensive review of this literature is beyond the scope of this paper (reviews can be found in, e.g., Cavallo and Noy, 2009; Hallegatte, 2014; Kousky, 2014).

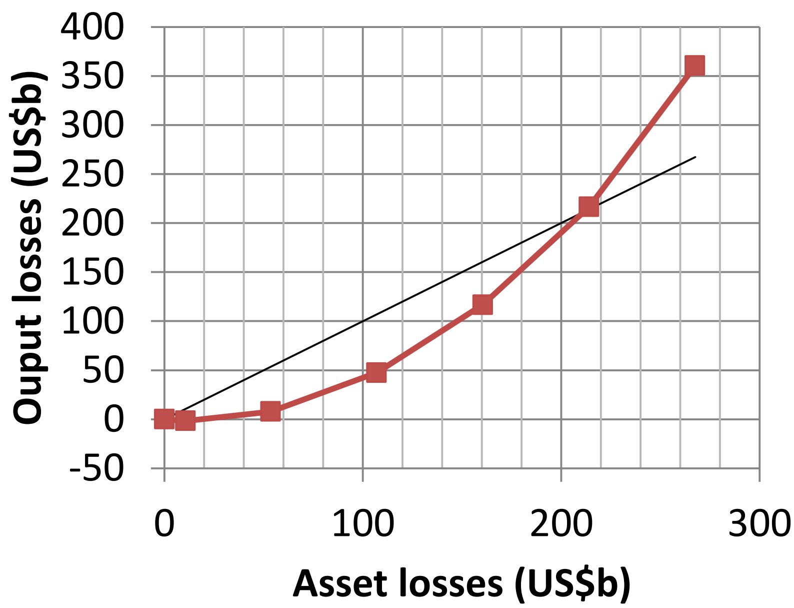

Figure 4: The link between asset losses and output losses, in Louisiana for disasters of increasing magnitude (but the same pattern as hurricane Katrina). Source: Hallegatte (2008).

As an illustration, Hallegatte (2014, 2008) use the Adaptive Regional Input-Ouput (ARIO) model calibrated on Louisiana to investigate the link between asset and output losses. The analysis concludes that total losses due to a disaster affecting Louisiana increase nonlinearly with respect to asset losses when the latter exceed $50 billion (see Figure 4). When asset losses are lower than $50bn, aggregated output losses are close to zero (even though the aggregation hides important disparities across sectors). Beyond $50 billion of asset losses, output losses increase nonlinearly. When asset losses exceed $200 billion, for instance, output losses are equal to asset losses.

2.3.2 A simple rule to assess total output losses

In the framework presented here, one dollar of direct loss in productive capital translates into more than the same amount of output losses. The instantaneous decrease in output is instead equal to the amount of asset losses multiplied by the *average* productivity of capital, which is about three times the marginal productivity of capital (r), possibly increased by a factor ($1+\alpha$) that represents ripple-effects.

$$\Delta Y(t_0) = \frac{1+\alpha}{\mu} r \Delta K \tag{8}$$

Assuming that output losses are reduced to zero exponentially, and that 95% of the losses are repaired in N years, then the output losses are also decreasing exponentially, with a characteristic time N/3; Output losses after t_0 are thus given by: [9]

$$\Delta Y(t) = \frac{1+\alpha}{\mu} r \Delta K e^{-\frac{t-t_0}{N/3}} \tag{9}$$

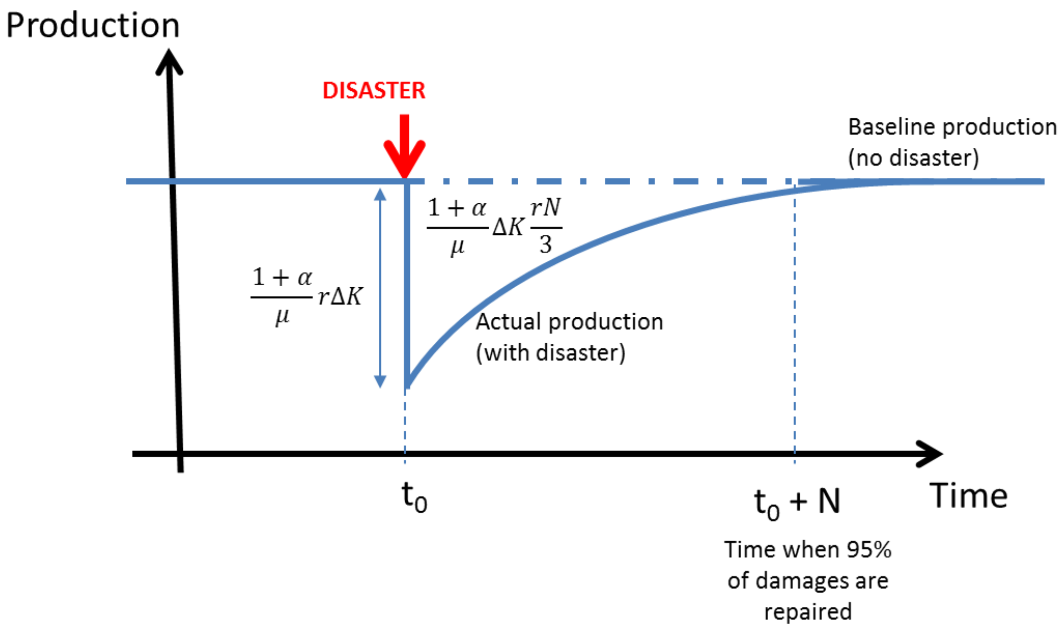

Figure 5: (Very) simplified representation of the return to "initial state" after a disaster. The area between the horizontal line and the actual production is the total loss of production and is given by Equation (10).

One difficulty is the fact that an economy affected by a disaster may never return to its initial situation: some activities may disappear permanently, while new sectors may appear. Hurricanes in La Réunion, a French island off the coast of Madagascar, in 1806 and 1807 led to a shift from coffee to sugar cane production, for instance. Also, "good" reconstruction may improve the quality and resilience of infrastructure and productive capital (see discussion of this effect in, among others, Benson and Clay, 2004; Skidmore and Toya, 2002). In this rule of thumb, however, we assess the cost of the disaster as the losses that occur if the economy returns to its initial state, leaving economic growth aside. A modeling exercise with an endogenous growth model (Hallegatte and Dumas, 2009) suggests that introducing even an optimistic version of this effect would not change results dramatically. Moreover, even if there is no "return to the initial situation," defining the "cost" as "the cost to return to the initial situation" provides a useful (and comparable) benchmark.

[9] In that case, a fraction *3/N* of remaining damages is repaired every year and remaining losses are given by an exponential. The characteristic time (also referred to as the e-folding time) is equal to *3/N* because $\exp(-3) \approx 0.05$ so that $\Delta Y(N) = 0.05\,\Delta Y(t_0)$.

With this reconstruction pathway, total *non-discounted* output losses $\overline{\Delta Y}$ are equal to (see Figure 5):

$$\overline{\Delta Y} = \int_{t_0}^{+\infty} \frac{1+\alpha}{\mu} r\Delta K e^{-\frac{t-t_0}{N/3}} dt = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{3} \qquad (10)$$

The parameter N is the reconstruction period and it can often be estimated by experts based on past experience.[10] Note that the reconstruction time is not the time when the observed GDP or output returns to its pre-disaster value, but may be much longer. Indeed, GDP and output are affected by other mechanisms, including changes in labor productivity, trade effects, other investments, and possibly the "stimulus effect" of the disaster. In this framework, as mentioned in Section 2.2.5, the stimulus effect is not accounted for in disaster consequences since it corresponds to benefits that could have been captured in the absence of the disaster, through a classical stimulus policy.

The length of the reconstruction period will depend on many characteristics of the affected economy, including (1) the capacity of the sectors involved in the reconstruction process (especially the construction sector); (2) the flexibility of the economy and its ability to mobilize resources for reconstruction (e.g., the ability of workers to move to the construction sector, see Hallegatte, 2008); (3) the openness of the economy and its ability to access resources (e.g., skilled workers and materials for reconstruction); (4) the financial strength of private actors, households and firms, and their ability to access financial resources for reconstruction, through savings, insurance claims, or credit; and (5) the financial strength of the public sector and its ability to access financial resources to reconstruct (see the very thorough analysis of financing options in developing countries in Mechler, 2004).[11]

Taking an example of a disaster that makes capital losses equal to $500 million, in a country with a 10% interest rate, with a reconstruction period that is likely to span over 3 years would lead to output losses equal to $150 million (i.e. 30% of direct capital losses).

In the context of Figure 4 (hurricanes in Louisiana), this rule of thumb reproduces model results, assuming that losses less than $50 billion can be repaired in one year, and that losses amounting to $100, $150, $200, and $250 billion can be repaired in 5, 10, 12, and 15 years, respectively.

With discounting at a rate r, the net present value of output losses is[12]:

$$\widetilde{\Delta Y} = \int_{t_0}^{+\infty} \frac{1+\alpha}{\mu} r\Delta K e^{-\frac{t-t_0}{N/3}} e^{-r(t-t_0)} dt = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{rN+3} \qquad (11)$$

2.4 Welfare losses and macroeconomic resilience

Losses in economic output do not directly affect people's welfare; for households, what matters most is consumption.[13] It is thus important to investigate how output losses translate into consumption losses

[10] Production losses also depend on the reconstruction pathway. Here we assume an exponential reconstruction; if the reconstruction is linear in N years, then Eq.(11) becomes $\overline{\Delta Y} = \frac{1+\alpha}{\mu} \Delta K \frac{rN}{2}$.

[11] Specific instruments such as contingent credit lines help with reconstruction financing. See for instance on the World Bank's Cat-DDO, http://treasury.worldbank.org/bdm/pdf/Handouts_Finance/CatDDO_Product_Note.pdf.

[12] The variable noted with $\tilde{x}$ are the net present value of the future fluxes of $x(t)$.

(Mechler, 2009). And since capital and output losses partly interact, it is incorrect to simply sum them to estimate welfare losses. In this section, we assess the aggregate consumption losses due to a disaster.

2.4.1 Aggregated consumption losses

Consider first a scenario in which all losses are repaired instantaneously by reducing consumption and directing all the goods and services that are not consumed toward reconstruction investments (this is a scenario where reconstruction capacity is infinite). In this theoretical scenario, there is no output loss since all asset damages are instantaneously repaired, and the reconstruction duration, N, is equal to zero in Eq. (11). There are however consumption losses, since consumption has to be reduced to reconstruct, and this reduction is equal to the reconstruction value (i.e. the replacement cost of damaged capital). In that case, the net present value of consumption losses ($\widetilde{\Delta C}$) are simply equal to the value of lost assets that need to be replaced (i.e., direct asset losses ΔK).

Consider now another scenario with no reconstruction, in which output losses are permanent (like in Figure 2) and all losses in output are absorbed by a reduction in consumption (but no share of income is used for reconstruction). In that case, consumption losses are equal to output losses (with no reconstruction), and N is equal to infinity in Eq. (11). The loss in consumption at t_0 is thus equal to $((1+\alpha)/\mu)r\Delta K$, see Eq. (7), and the net present value (discounted at the rate *r*) of consumption losses is $((1+\alpha)/\mu)\Delta K$. Consumption losses and welfare losses are thus larger than the value of lost assets in a no-reconstruction scenario (at least if $\alpha > 0$).

In the instantaneous reconstruction scenario, consumption losses are equal to the share of consumption needed to repair and rebuild, i.e. to asset losses ΔK. In the no-reconstruction scenario, consumption losses are equal to output losses $((1+\alpha)/\mu)\Delta K$, i.e. larger than direct losses ΔK.[14] As a result, consumption (and welfare) losses are magnified when reconstruction is delayed or slowed down.[15] And in all realistic scenarios where reconstruction takes some time (from months for small events to years for large-scale disasters), welfare losses are larger than direct losses.

For intermediate scenarios (with reconstruction over a given period), the actual welfare loss is the sum of the net present value of reconstruction cost (i.e. the direct capital cost) and the net present value of indirect (output) losses.

[13] Another major issue is the potential loss of jobs, which affect households. Loss of assets and reduction in output may lead to job losses. Here, we assume that the consequence of job losses can be represented through consumption losses, even though unemployment can have social and human consequences that go beyond the loss of income and consumption (e.g., exclusion, loss of skills).

[14] The reality is more complex that what has been described here because not all output losses are translated into consumption losses. In practice, the loss in output changes the terms of the inter-temporal investment-consumption trade-off and translates into ambiguous instantaneous changes in consumption and investment. But the main conclusions of the analysis are not affected by this complexity.

[15] The fact that rapid reconstruction is better for welfare than slow reconstruction – or equivalently, that reconstruction has a return that is much higher than that of "normal investments" and the interest rate – explains why reconstruction is usually a priority and crowds out consumption and other investments in the affected region.

The reconstruction phase, and the economic recovery pace, will ultimately determine the final welfare cost of the natural disasters. If 95% of reconstruction is done exponentially over N years, the present value of consumption losses is equal to:

$$\widetilde{\Delta C} = \int_{t_0}^{+\infty} \left(\frac{1+\alpha}{\mu} r \Delta K e^{-\frac{t-t_0}{N/3}} + \Delta K e^{-\frac{t-t_0}{N/3}} \frac{3}{N} \right) e^{-rt} dt = \Delta K \frac{\frac{1+\alpha}{\mu} r + 3/N}{r + 3/N} \tag{12}$$

Note the two extreme cases:

- As N tends toward zero, $\widetilde{\Delta C}$ tends to ΔK.
- As N tends toward the infinity (no reconstruction), $\widetilde{\Delta C}$ tends to (1+α)ΔK/μ.

Also, if the productivity of the affected capital is equal to the marginal productivity of capital, i.e. $\frac{1+\alpha}{\mu} = 1$, then the loss of consumption becomes independent of the reconstruction duration. This is similar to a balanced growth pathway along which the welfare produced by one additional unit of investment is equal to the welfare produced by one additional unit of consumption (so that the consumer is indifferent between investment and consumption).

The interest rate is a component of macroeconomic resilience: the welfare impacts of disasters will be higher in countries where capital is scarce and the interest rate (and the marginal productivity of capital) is high. Also, consumption losses will be larger where capital returns are decreasing rapidly (i.e. where μ is large).

Simplifying Eq. (12), we have:

$$\widetilde{\Delta C} = \frac{1 + \frac{1+\alpha}{3\mu} rN}{1 + \frac{rN}{3}} \Delta K = \Gamma \cdot \Delta K \tag{13}$$

So in that case, the capital losses are simply increased by an "amplifying factor" Γ that depends on the interest rate, the reconstruction duration, the decreasing returns of capital, and the magnifying effect of ripple-effects in the economic system. Taking again the example of a disaster that makes capital losses equal to $500 million, in a country with a 10% interest rate, with a reconstruction period that is likely to span over 3 years, the discounted loss of consumption is $606 million, which is 21% larger than asset losses.

2.4.2 Defining macroeconomic resilience

In this framework, *macro-economic resilience* is the ability to maintain aggregated consumption losses ($\widetilde{\Delta C}$) as small as possible, *for a given amount of capital losses* (ΔK), i.e. minimizing the amplifying factor Γ (see also Figure 1).

Therefore, macroeconomic resilience (to one given event) can be defined as:

$$R^{\text{macro}} = \frac{\Delta K}{\widetilde{\Delta C}} = \frac{1}{\Gamma} \tag{14}$$

Here macro-economic resilience is defined in a way that makes it independent of other determinants of the overall welfare risk from disasters, namely the hazard, exposure and vulnerability. In other terms, the consumption impact can be reduced by reducing exposure and vulnerability of people and assets (i.e. reducing ΔK) or by increasing macroeconomic resilience R^{macro}.

Assuming that the interest rate and the decreasing returns of capital are fixed, this factor is determined by two parameters, namely $1/\alpha$ and 1/N. The former is an *instantaneous resilience*[16], i.e. the ability to limit the magnitude of the immediate loss of income for a given amount of capital losses. The latter is *a dynamic resilience*, i.e. the ability to reconstruct and recover quickly.

To measure the macro-resilience of a country $\overline{R^{\text{macro}}}$ (not to a specific event but to all hazards in the country), one would need to estimate the macroeconomic resilience to all possible hazards (i.e., earthquakes of different magnitudes, hurricanes of different intensities, floods of various magnitudes, etc.), and calculate a weighted average of the amplifying factor Γ, weighted by the probability and the direct losses ΔK of each hazard.

If τ is the return period of a category of event (i.e., $\tau = 1/p$, where p is the annual probability of occurrence), then an estimate would be:

$$\overline{R^{\text{macro}}} = \frac{\int_0^{+\infty} \frac{1}{\tau} \Delta K(\tau) d\tau}{\int_0^{+\infty} \frac{1}{\tau} \widetilde{\Delta C}(\tau)\, d\tau} = \frac{\int_0^{+\infty} \frac{1}{\tau} \Delta K(\tau) d\tau}{\int_0^{+\infty} \frac{1}{\tau} \Delta K(\tau) \Gamma(\tau)\, d\tau} \tag{15}$$

To make this calculation practical, one can recommend focusing on three return periods: one year, 10 years, and 100 years and to estimate the amount of capital losses (ΔK_1, ΔK_{10}, and ΔK_{100}) that can be estimated for these return periods, together with realistic values for α and N. An estimate of macro-resilience is then:

$$\overline{R^{\text{macro}}} = \frac{\Delta K_1 + \frac{1}{10} \Delta K_{10} + \frac{1}{100} \Delta K_{100}}{\Delta K_1 \Gamma_1 + \frac{1}{10} \Delta K_{10} \Gamma_{10} + \frac{1}{100} \Delta K_{100} \Gamma_{100}} \tag{16}$$

In the presence of multiple risks (earthquake, storms, etc.), the calculation should be done for all categories of risks, and weighted accordingly.

[16] As already mentioned, this instantaneous resilience is linked to the "static" resilience used by other authors (Pant et al., 2014; Rose, 2013). However, the quantitative definitions are different. Rose defines the static resilience as the (relative) difference between actual output losses and the output losses in the absence of any adaptation (e.g., substitution, rescheduling) to the shock. He shows that adaptation options can make static resilience reaches high values (e.g., 70% in the case of a sea port in (Rose and Wei, 2013)). It is not trivial to translate this value for static resilience into a value for instantaneous resilience (or for the parameter α).

3 Impacts on households and microeconomic resilience

To estimate the welfare impact of a macroeconomic loss in consumption, it is necessary to account for the distributional impacts of the disaster, and for the ability of households to cope with the shock (see for instance Adger et al., 2002; Morris et al., 2002; Adger, 1999, and a review of "resilience strategies" of households in Rose, 2013, Table I). The 2005 landfall of Katrina on New Orleans has renewed attention on the larger weather vulnerability of the poorest communities, and on the inequality-widening effect of disasters (Atkins and Moy, 2005; Tierney, 2006). Rodriguez-Oreggia et al. (2009) show that municipalities affected by disasters in Mexico see an increase in poverty by 1.5 to 3.6 percentage points. Often, the poorest have few assets to lose in a disaster and the impact on their welfare is therefore invisible in aggregated economic statistics.[17] If the aim of the assessment is to look at welfare impacts, focusing only on economic aggregates can be misleading.

To assess welfare impacts, we thus need to account for the heterogeneity in consumption losses, and for the pre-disaster income distribution. To perform a detailed analysis, it would be necessary to consider the full distribution of income or wealth in the affected area, the full distribution of impacts of the disaster, and the correlation between the two (i.e. the differential likelihood of being affected by a given amount of losses, depending on the income level). Because it would make the exposition complicated and because lack of data makes it impossible to perform such an analysis, this section will present a simplified analysis based on a few household categories only.

In practice, we will be using only four categories of households depending on whether: (i) they are poor or not; and (ii) they are affected by the disaster of not. All poor households are assumed to have the same income and wealth; as do non-poor households. The framework is flexible regarding the definitions of "poor" and "non-poor."[18] In particular, one can decide to focus on extreme poverty by defining the poor following the World Bank poverty line ($1.25 per day) or to use a broader definition of the poor that is relevant for disaster analysis (e.g., the population with no access to financial instruments, or the population that is "vulnerable" to falling back into poverty[19]). All the calculations that are proposed in this section are theoretically possible in a more complicated framework with more than two categories. Note that in this analysis, we look at the welfare impact for the affected population without considering potential gains in other regions or countries, for instance if non-affected areas capture market shares lost by the affected region.

3.1 Ex-ante welfare impacts

We assume first that all affected poor (respectively non-poor) households suffer from the same amount of losses (this assumption will be relaxed later on), and losses are assumed to be proportional to their income. These are strong assumptions for two reasons. First, poor households are often more

[17] See an example on floods in Mumbai in (Hallegatte et al., 2010) showing that the impact on marginalized population is small in absolute terms, even though the effect of their welfare may dominate other disaster effects.
[18] However, since the main difference between poor and non-poor will be the marginal utility of income, monetary definitions of poverty appears more appropriate than non-monetary definitions, in this very context.
[19] See a discussion on the World Bank website: http://go.worldbank.org/R048B34JF0.

vulnerable than rich ones, so they are likely to lose a larger fraction of their assets than rich households.[20] Second, disaster losses are highly heterogeneous and different households are affected very differently (see Section 3.2).

Before the impact, the welfare in the affected area is given by:

$$W^- = n_p^a u(\widetilde{c_p}) + n_r^a u(\widetilde{c_r}) \tag{17}$$

Where n_p^a and n_r^a are the number of poor and non-poor households in the affected area, and $\widetilde{c_p}$ and $\widetilde{c_r}$ are their consumption (note that all values noted with in $\tilde{x}$ are for the net present value of the future flux, not the instantaneous value at time t). The function u is a "welfare function" that links the net present value of consumption with individual welfare. Using the net present values of consumption to assess welfare is a strong simplification, which is acceptable only if households can smooth the shock over time and if the shock remains relatively limited compared with consumption; these assumptions are thus relaxed in Section 3.2.

After the shock, but before any transfers, the welfare becomes:

$$W^+ = n_p^a u(\widetilde{c_p} - \widetilde{\Delta c_p}) + n_r^a u(\widetilde{c_r} - \widetilde{\Delta c_r}) \tag{18}$$

Where $\widetilde{\Delta c_p}$ and $\widetilde{\Delta c_r}$ are the household level consumption losses due to the disaster (also in net present value of the future flux of consumption loss). Since we are looking at the net present value of consumption (and net present value of the consumption loss), it is likely that $\widetilde{\Delta c_p}$ and $\widetilde{\Delta c_r}$ are small compared with $\widetilde{c_p}$ and $\widetilde{c_r}$, and the nonlinear terms become negligible:

$$\Delta W \approx n_p^a u'(\widetilde{c_p})\widetilde{\Delta c_p} + n_r^a u'(\widetilde{c_r})\widetilde{\Delta c_r} \tag{19}$$

Note that these consumption losses can be due to the direct impact of the disaster on households' productive assets (including their home) or to indirect impacts through the impact on firms (and employment and capital gains) and through government-provided services.[21] If we assume linearity of losses to pre-disaster income, we have $\widetilde{\Delta c_p} = \varphi\widetilde{c_p}$ and $\widetilde{\Delta c_r} = \varphi\widetilde{c_r}$. We have the total income in the area $\widetilde{C^a} = n_p^a\widetilde{c_p} + n_r^a\widetilde{c_r}$, and the total loss of income equal to $\widetilde{\Delta C} = n_p^a\widetilde{\Delta c_p} + n_r^a\widetilde{\Delta c_r}$. We thus have $\varphi = \widetilde{\Delta C}/\widetilde{C^a}$ and thus:

$$\Delta W \approx \left[n_p^a\widetilde{c_p}u'(\widetilde{c_p}) + n_r^a\widetilde{c_r}u'(\widetilde{c_r})\right]\frac{\Delta C}{C^a} \tag{20}$$

[20] One important consideration we are not taking into account here is the differentiated ability of poor and non-poor households to save in non-tangible assets such as financial products, which are less exposed to natural hazards and can be more easily diversified (spatially and sectorally). If poor households save in kind while non-poor save through financial product, the vulnerability of the former will be larger than that of the latter, and the distribution of disaster losses will not be proportional to income or wealth. In the analysis of hurricane Mitch in Honduras (Carter et al., 2007), poor households are found to be affected less often than rich households, but they lose a larger fraction of their assets if they are affected.

[21] The impact through government-provided services depends on the ability of the government to fund reconstruction and the need to reallocate budget resources from public services to reconstruction; this will depend on the public sector vulnerability to disasters (Aakre et al., 2010; Mechler, 2004; Mechler et al., 2006).

The two parameters $u'(\widetilde{c_p})$ and $u'(\widetilde{c_r})$ can be interpreted as distributional weights, classically used to compare losses and benefits that affect households of different incomes and wealth (Fleurbaey and Hammond, 2004).

We now define the aggregate income of the poor in the affected area as $\widetilde{C_p^a} = n_p^a \widetilde{c_p}$ and the aggregate income of the non-poor in the affected area as $\widetilde{C_r^a} = n_r^a \widetilde{c_r}$. Then, we have:

$$\Delta W \approx \left[\frac{\widetilde{C_p^a}}{\widetilde{C^a}}\left(u'(\widetilde{c_p}) - u'(\widetilde{c_r})\right) + u'(\widetilde{c_r})\right]\widetilde{\Delta C} \tag{21}$$

The relationship can be simplified further as:

$$\Delta W \approx \overbrace{[\omega_a \Delta u' + u'(\widetilde{c_r})]}^{\theta}\,\widetilde{\Delta C} \tag{22}$$

The term θ translates the impact on aggregated consumption into the impact on welfare, and it depends on the level of wealth (and equality) in the country, and on the differential exposure of the poor and the non-poor.

The variable $\Delta u' = u'(\widetilde{c_p}) - u'(\widetilde{c_r})$ is the difference in the pre-disaster marginal utility of income of the poor vs. the non-poor and thus is positive and a measure of inequality. It depends on inequality within a country: if there is a large income difference between the poor and the non-poor, then this parameter becomes larger.

The parameter $\omega^a = \widetilde{C_p^a}/\widetilde{C^a}$ is the fraction of the affected consumption that is consumed by the poor, and is a measure of the relative exposure of the poor when compared with the rest of the population. Here we simplify the analysis by also assuming that this fraction is the relative exposure in terms of assets (i.e. the fraction of affected assets that belong to the poor).[22] In that case, ω^a can be rewritten as K_p^a/K^a, where K^a is the exposed and affected capital and K_p^a is the affected capital that belong to the poor (or from which the poor derive their income in the case of public assets).

The parameter ω^a describes the specific vulnerability of the poor in a country:

- If disasters are "income-blind", i.e. they affect the poor and the non-poor equally, then $\omega^a = \widetilde{K_p^a}/\widetilde{K^a} = \widetilde{K_p}/\widetilde{K} = \omega$, i.e. the distribution of wealth or income in the country.
- If disasters affect only the poor, then $\omega^a = 1$.
- If disasters affect only the rich, then $\omega^a = 0$.

Since we have $\Delta u'$>0, the aggregate impact on welfare will be larger than the aggregate impact on consumption if ω^a is large, i.e. if disasters affect mostly the poor. In that case, the higher exposure of the poor acts as a magnifying effect on the welfare impact of disasters (it increases θ). And if the inequality is higher, then this magnifying effect of the differential exposure on welfare will increase (θ

[22] This is a simplification since inequality in terms of assets is different (often larger) than inequality in terms of consumption.

increases further). Similarly, the overall income level in the country (here represented by $u'(\widetilde{c_r})$) affects resilience: increasing income reduces the marginal utility of consumption (both $u'(\widetilde{c_p})$ and $u'(\widetilde{c_r})$), and thus decreases the welfare vulnerability θ (and thus the welfare impact of any disaster).

3.2 Instantaneous impacts, basic needs, and smoothing

But assuming that utility only depends on the net present value of future consumption is appropriate only if we assume that households have the capacity to smooth the shock over time, through self-insurance (i.e. savings), market insurance (i.e. paying a premium every year instead of the losses when they occur), or full access to credit (and that disasters remain relatively limited in magnitude). In many countries, this is not an acceptable assumption[23], so it is important to investigate impacts in the situation without smoothing.

To do so, we have to account for the impact of immediate consumption and income. To approximate this impact, we assume that the households with “negative income” the year of the shock (i.e., those for which immediate income losses are larger than annual income[24]) are unable to fulfil their basic needs and suffer from losses that go beyond the impact of a change in aggregate consumption.

We will use the impact on these households as an indicator of the impact that cannot be smoothed over time. We assume that for these households, the shock is mostly related to the immediate impact, not to the net present value of the flux of consumption losses, and that they suffer from economic and non-economic losses (reduction in food intake, health effects, stunting on children, etc.) that are monetized independently of the size of their loss. This is a strong simplification of the reality – which consists of a continuum of intertwined impacts on wealth and instantaneous consumption – but it allows including in the calculation in a simple way an essential component of disaster impacts.

Since we are looking at a nonlinear process, it would be highly misleading to assess the impact on welfare using the average impact of the disaster. As already stated, direct losses of disasters are heterogeneous. Investigating the 2004 hurricane season in Florida, (McCarty and Smith, 2005) find that – in their study area – 74% of housing units were damaged, but only 2.2% were totally destroyed while 40% had only minor damages. Looking at the Northridge earthquake in 1994 in Los Angeles, (Tierney, 1997) finds that the median dollar loss from physical damage is US$5,000 while the average loss is US$156,000.

In Appendix C, we calculate the fraction X of households who are experiencing negative income the year of the disaster.[25] To do so, we assume that direct losses are distributed as a Gumbel distribution (a

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[23] (Carter et al., 2007) find evidence of asset smoothing among the poorest households in Ethiopia following the drought in 1998-2000, suggesting that households prefer to support a large decrease in consumption when the shock hits than reducing their asset stock too much.

[24] In this section, the income loss during the first year is given by the reduced *output* of capital, but the entire asset losses are not accounted for as a one-year income loss. In other terms, the asset losses are “amortized” over the reconstruction period.

[25] Note that we do not remove the value of asset losses from their income; instead we calculate the lost income from lost assets, and remove this lost income from their pre-disaster income.

classic assumption for extreme events), and we introduce a measure of direct losses heterogeneity through h. The parameter h is equal to the ratio of the household asset loss median to the household asset loss mean (h is generally lower than one, and low values of h correspond to high heterogeneity).

This parameter depends on the hazard itself: some events affect many households more homogeneously than others (for instance, flood losses are particularly heterogeneous and would have a lower h than droughts). It also depends on the economic structure: in a diversified economy, losses are more homogeneous. For instance, if households have multiple income sources, they are more likely to lose a smaller share of their income if one activity is particularly affected (e.g., yields during a drought), and h will be higher.

The resulting fraction X is given by:[26]

$$X = \Theta((1+\alpha)V\,,h) \tag{23}$$

With

$$\Theta(x,h) = \left(1 - e^{-e^{\frac{1}{1-h}\left(-(\gamma+\chi)\frac{1}{x}+h\gamma+\chi\right)}}\right) \tag{24}$$

The parameter V is the "vulnerability" of affected capital, i.e. it is defined as the fraction of the affected capital that is lost because of the disaster: $\Delta K = K^a V$.

Figure 6 shows the fraction of households with negative income the year of the shock, as a function of the size of the shock, and with different assumptions regarding h. For homogeneous shocks (i.e., large values of h), there are initially few households with negative incomes for small disasters, but the number increases quickly when production loss approaches annual production. For heterogeneous shocks (i.e., low value of h), the number of households with negative income grows rapidly for a low amount of aggregate losses, but it saturates at higher values.

Assuming that $h = 50\%$ or lower, Figure 6 shows that it would be highly misleading to linearize this function, as it behaves very differently in three segments: (1) for small aggregate losses (<10% of the annual income of affected households), no household suffers from negative income; (2) for larger losses (between 10 and 50% of annual income), the number of households with negative income grow very rapidly; (3) for very large losses (larger than 50% of annual income), this number stabilizes around 50 percent.

[26] The parameter γ is the Euler–Mascheroni constant, approximately equal to 0.5772, and $\chi = \ln(\ln(2))$.

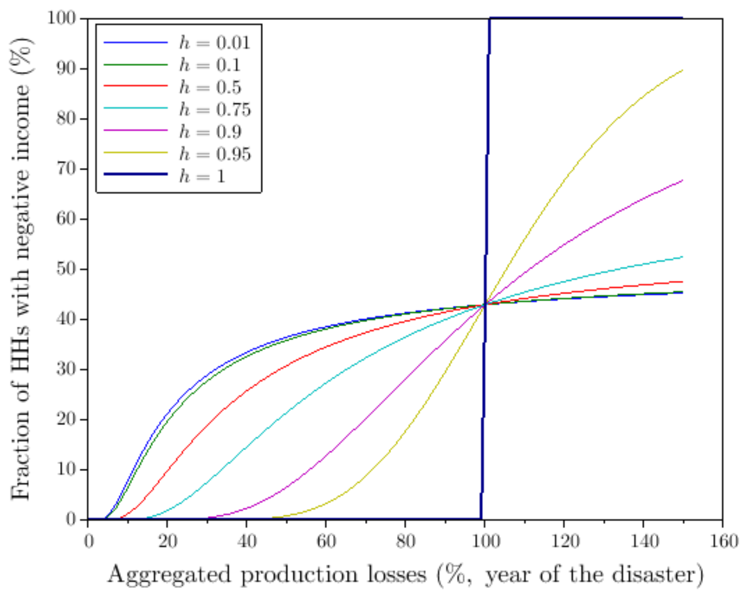

Figure 6. Fraction of households with negative income the year of the shock, as a function of the magnitude of the shock, expressed as the ratio of aggregate production loss at the time of the shock divided by aggregate annual production (in the affected region).

If households have no smoothing option and assistance (an extreme assumption, even for the poorest), those with negative income will suffer high welfare losses, and their lives can be threatened. For that reason, we add in the welfare cost a term:

$$\Delta W_{\text{shock}} = n^a \Delta w_{max} \Theta((1+\alpha)V\,, h) \qquad (25)$$

Where Δw_{max} is the maximum loss of welfare a household can suffer from (which depends on the social protection system, see below). In the absence of social protection and if lives are threatened, one possible higher bound for Δw_{max} is $n_h \text{VSL}$, where n_h is the number of individuals in a household and VSL is the "value of a statistical life."

The parameter Δw_{max} can also encompass the cost of non-economic impacts on the most affected, such as stunting for children (if food intake has to be reduced), loss of education (if children are taken out of school), and the possibility of household-level poverty traps due more generally to lack of assets (Carter and Barrett, 2006; Carter et al., 2007; Dercon, 2004).

This result applies only to the households who cannot smooth the shock thanks to savings, borrowing, and insurance. To take this into account, we introduce an additional parameter Ψ that describes the *ability to smooth shocks thanks to savings, borrowing, and insurance*.

If there is perfect smoothing ($\Psi = 1$), the impact on welfare described in Section 3.1 holds. If smoothing is not perfect, then the instantaneous impacts on income may matter, and we have to take it into account. In practice, we assume that the instantaneous impacts apply only to a share $(1-\Psi)$ of the households:[27]

$$\Delta W_{\text{shock}} = n^a \Delta w_{max}(1-\Psi)\Theta((1+\alpha)V\,,h) \tag{26}$$

With a partial ability to smooth shocks, the total welfare impact is the sum of (1) the impacts on inter-temporal welfare from a reduction in wealth ($\widetilde{\Delta C}$), that can be approximated as a linear shock and is described in Section 3.1. and given by Eq. (22); and (2) a non-marginal instantaneous shock on income that affects basic needs and is measured in this section through Eq. (26). The result can be approximated as:

$$\Delta W \approx \left[\omega_a \Delta u' + u'^{(\widetilde{c_r})}\right]\widetilde{\Delta C} \;+\; n^a \Delta w_{max}(1-\Psi)\Theta((1+\alpha)V\,,h) \tag{27}$$

3.3 Social protection, transfers and welfare impacts

To assess the ex post situation and the final impact on people's welfare, we need to account for social protection and transfers. To assess the ex post welfare impacts, we need to include in the analysis the population that shares the risks, i.e. the country population for national social schemes and the world population for international support and foreign aid. Since the impact of almost all disasters is negligible at the global level, we will neglect the impact on the global population and only consider the country population.

The benefits from social protection and other government action are threefold:

- Social protection may put a limit to the welfare losses a household can suffer from, i.e. reduce Δw_{max}. It is the case for instance if basic services (housing, health, or food) are provided at no cost to the poorest or those who have lost everything in the disaster.
- Social protection and other government action may mitigate instantaneous income losses and can help households smooth shocks over time (e.g., through facilitated access to credit and insurance, and other financial inclusion policies), so that fewer households suffer from an instantaneous income loss that is larger than their annual income, i.e. it can increase Ψ.
- Social protection may transfer some of the losses, even for those who are affected but have not lost all of their annual income, i.e. it can affect the impact on the net present value of the consumption flux in Eq. (18) (i.e., $\widetilde{\Delta c_p}$ and $\widetilde{\Delta c_r}$). It is the case if lost income is replaced by cash transfers (or cash-for-work programs) for the most affected, paid by the rest of the population, or in the presence of subsidized insurance. It is also the case if foreign aid is distributed to the population (in kind or in cash).[28]

[27] It is well documented that the ability to smooth shocks is very different for poor and non-poor households. An option could be to assume that non-poor households are perfectly able to smooth shocks ($\Psi_r = 1$) while poor households can unable to do so ($\Psi_p = 0$). In that case, Ψ would be the fraction of non-poor in the country. Alternatively, Ψ can be calibrated using financial inclusion data and a criteria on the stock of assets needed to be able to smooth shocks (Carter et al., 2007; World Bank, 2013b).

[28] See the impact of aid on aggregate consumption in Honduras after disasters in Mechler (2009, Fig. 5).

The two first impacts can be accounted for through changes in Δw_{max} and Ψ. The third requires analyzing the four categories of households depending on whether they are affected or not, and whether they are poor or not. We assume that a percentage σ of the consumption loss is shared across the country, and a fraction (1-σ) remains with the directly affected population. When the losses are shared across poor and non-poor, it is assumed that they are shared proportionally to income (i.e. rich people pay more than poor people, in a linear manner). The resulting losses of consumption are presented in Table 1.

		Affected	Non-affected
Poor	No insurance	$\frac{\widetilde{\Delta C}}{\widetilde{C^a}}\widetilde{c_p}$	0
	With insurance	$\left(\frac{\sigma}{\tilde{C}}+\frac{1-\sigma}{\widetilde{C^a}}\right)\widetilde{c_p}\widetilde{\Delta C}$	$\frac{\sigma}{C}\widetilde{c_p}\Delta C$
Non-poor	No insurance	$\frac{\widetilde{\Delta C}}{\widetilde{C^a}}\widetilde{c_r}$	0
	With insurance	$\left(\frac{\sigma}{\tilde{C}}+\frac{1-\sigma}{\widetilde{C^a}}\right)\widetilde{c_r}\widetilde{\Delta C}$	$\frac{\sigma}{C}\widetilde{c_r}\Delta C$

Table 1: Distribution of losses in the four categories of households and two scenarios (with and without insurance and risk sharing).

Under the same assumptions as in Section 3.1, we have:

$$\Delta W \approx \left[n_p^a u'(\widetilde{c_p})\left(\frac{\sigma}{\tilde{C}}+\frac{1-\sigma}{\widetilde{C^a}}\right)\widetilde{c_p} + n_r^a u'(\widetilde{c_r})\left(\frac{\sigma}{\tilde{C}}+\frac{1-\sigma}{\widetilde{C^a}}\right)\widetilde{c_r} + n_p^n u'(\widetilde{c_p})\frac{\sigma}{\tilde{C}}\widetilde{c_p} + n_r^n u'(\widetilde{c_r})\frac{\sigma}{\tilde{C}}\widetilde{c_r}\right]\widetilde{\Delta C} \qquad (28)$$

This relationship can be rewritten as:

$$\Delta W \approx [\Delta u'\,(\sigma\omega + (1-\sigma)\omega^a) + u'(\widetilde{c_r})]\widetilde{\Delta C} \qquad (29)$$

In this relationship, the benefits from social protection arise from the fact that it transfers losses from the poor to the rich; the classical benefits from risk sharing (i.e. smoothing losses) are taken into account through the reduction of the fraction of households who have negative income (see previous section).[29]

In sum, the relationship is:[30]

$$\Delta W \approx [\Delta u'(\sigma\omega + (1-\sigma)\omega^a) + u'(\widetilde{c_r})]\frac{1+\frac{1+\alpha}{3\mu}rN}{1+\frac{rN}{3}}K^a V + n^a \Delta w_{max}(1-\Psi)\Theta((1-\sigma)(1+\alpha)V\,,h) \qquad (30)$$

[29] Note that this is an important simplification: the individual benefit from insurance is the reduction of the number of households with negative income (assumed to suffer from large economic and non-economic losses), not the more moderate effect of smoothing economic losses for other households. This assumption is clearly more satisfying for developing countries than for developed countries.

[30] Note that transfers also affect the proportion of population with negative income the year of the shock.

3.4 Defining microeconomic resilience

Micro-economic resilience is defined as the ability of an economy and society to minimize household welfare losses ΔW for a given level of aggregate consumption losses ($\widetilde{\Delta C}$) (see Figure 1). As such microeconomic resilience (to a given event) can be defined as:

$$R^{\text{micro}} = \widetilde{\Delta C} / \Delta W \tag{31}$$

This definition ensures that microeconomic resilience is independent of macroeconomic resilience[31] and other determinants of the overall welfare risk from disasters (i.e., hazard, exposure and vulnerability).

For a given event, we have:

$$\Delta W = \frac{1}{R^{\text{micro}}} \frac{1}{R^{\text{macro}}} \Delta K = \frac{1}{R^{\text{micro}}} \frac{1}{R^{\text{macro}}} K^a V \tag{32}$$

As a result, the welfare risk can be reduced by reducing exposure and vulnerability of people and assets (i.e. reducing ΔK) or by increasing macroeconomic resilience (i.e. decreasing $\widetilde{\Delta C}$ for a given level of ΔK) or by increasing microeconomic resilience (i.e. decreasing ΔW for a given level of $\widetilde{\Delta C}$).

To calculate the microeconomic resilience of a country $\overline{R^{\text{micro}}}$ (a resilience that is not related to one given event, but to all hazards), one needs to calculate the welfare losses for the set of possible disasters, with their return periods, as was done for macroeconomic resilience:

$$\overline{R^{\text{micro}}} = \frac{\int_0^{+\infty} \frac{1}{\tau} \widetilde{\Delta C}(\tau) d\tau}{\int_0^{+\infty} \frac{1}{\tau} \Delta W(\tau) d\tau} \tag{33}$$

And as was suggested then, it is also possible to select a few possible events with different return periods, and to calculate the microeconomic resilience based on these few events:

$$\overline{R^{\text{micro}}} = \frac{\widetilde{\Delta C}_1 + \frac{1}{10}\widetilde{\Delta C}_{10} + \frac{1}{100}\widetilde{\Delta C}_{100}}{\Delta W_1 + \frac{1}{10}\Delta W_{10} + \frac{1}{100}\Delta W_{100}} \tag{34}$$

To account for different categories of disasters (earthquakes, storms, etc.), it is needed to do the same analysis for each hazard and to take the weighted sum to calculate the total resilience.

4 Welfare disaster risk and economic resilience

To reduce the welfare disaster risk (i.e. the potential for negative impact of natural disasters on population welfare), a first approach is to reduce the direct impacts on the economic systems, using for instance better coastal protections and stricter building norms. A complementary approach consists of reducing output losses through an increase in the resilience of the socio-economic system, using for instance insurance schemes or government support to the affected population. The welfare cost of a

[31] Note that they can have common determinants, such as insurance penetration and social protection systems.

disaster does not depend only on either the physical characteristics of the event or its direct impacts, but also on many other properties of affected economies and societies (see Figure 1).

Depending on the ability of the economy to cope, recover and reconstruct, the reconstruction will be more or less difficult, and its welfare effects smaller or larger. This ability, which can be referred to as the *macro-economic resilience* of the economy to natural disasters, is an important parameter to estimate the overall vulnerability of a population. Here, *macroeconomic resilience* is decomposed into two components: *instantaneous resilience*, i.e. the ability to limit the magnitude of the immediate loss of income for a given amount of asset losses; and *dynamic resilience*, i.e. the ability to reconstruct and recover quickly.

Also, welfare impacts will depend on the *microeconomic resilience*, which depends on the distribution of losses across households (especially households with different wealth), the vulnerability of the households, i.e. their pre-disaster income and their ability to smooth shocks over time, and on the social protection system, i.e. the mechanisms to share risks and protect the most vulnerable in a country.

These two concepts of resilience can be defined for a given event, or more generally for a country and all the hazards the country faces. Doing the latter is much more demanding, as it requires investigating all possible hazards and assessing their consequences in terms of asset losses and welfare impacts.

From these two concepts of resilience, one can define *economic resilience*, as a combination of micro and macro-economic resilience.[32] Beyond the calculation of an indicator for economic resilience, this analysis provides an interesting framework to think about risk management policies. Overall, the welfare impact of disasters depends on:

- The probability of occurrence of disasters (p for various events);
- The exposure to possible disasters, represented by:
  - The total affected capital (K^a) and the number of affected households (n^a); for a given amount of direct losses, resilience is higher if these losses are distributed across a large population (in other terms, resilience increases when n^a increase, *ceteris paribus)*.
- The vulnerability of the exposed capital V (or equivalently, total asset losses ΔK).
- The macroeconomic resilience that depends on:
  - The interest rate and marginal capital productivity (r);
  - The reconstruction duration in years (N), which depends on the ability of the economy to mobilize financial and technical resources to rebuild;
  - The ripple-effects that amplify (or diminish) instantaneous production losses (α), which depend on the idle resources available in the economy, on the redundancy of infrastructure and other networks, and on firms' ability to cope with shocks.
- The microeconomic resilience that depends on:

[32] When looking at the resilience to one given event, economic resilience is simply the product of microeconomic and macroeconomic resilience (see Eq. (32)). If one investigates resilience to all hazards, then the calculation is more complicated and microeconomic and macroeconomic resilience cannot be simply multiplied, since they are very likely to be correlated. In practice, one needs to assess economic resilience for each hazard and take a weighted average, like for microeconomic resilience in Eq. (33).

- The level of income in the country (represented with $u'(c_r)$);
- The inequality level (represented with $\Delta u'$), with countries with higher inequality being less resilient to disasters;
- The "poverty bias" of disasters, i.e. the relative exposure of the poor (ω^a), compared with the share of assets owned by the poor (ω).
- The heterogeneity in direct losses across households (h), which depends on the hazards (e.g., high winds have often impacts that are less concentrated than floods), but also on the diversification of the economic system (e.g., if households have multiple sources of income, it is more likely that losses will be shared among more households).
- The ability of households to smooth income shocks over time thanks to insurance, savings and borrowing (Ψ);
- The maximum loss of welfare that an household can suffer from, which is linked to the provision of basic services for the poorest (Δw_{max});
- The amount of risk-sharing in the economy, represented by σ, and that depends on social protection systems and availability of insurance;

Some of the simplifications in this framework can be questioned. In particular, four of them deserve specific attention.

First, the vulnerability V is assumed identical for poor and non-poor households, while it is well known that the assets of the poor are more vulnerable: more of them are in tangible form (e.g., more as houses, small equipment or even cattle, and less as financial assets in a bank) that can be directly affected and are more difficult to diversify. Moreover, the tangible assets of the poor are often more vulnerable (e.g., lower quality houses that can be completely wiped out by wind).

Second, the ability of individual firms to cope with the shock and continue to produce in the disaster aftermath – the static resilience of (Rose, 2009) that is analyzed in, e.g., Rose and Wei (2013) or Rose et al. (2007a) – is summarized in the parameter α and determines the *instantaneous resilience*. Various methodologies have been proposed to assess these parameters, using input-output or general equilibrium models (Hallegatte, 2014; Rose and Wei, 2013; Santos and Haimes, 2004) or explicit modelling of supply-chains (Battiston et al., 2007; Henriet et al., 2012). But more work is needed to assess this resilience based on the data and indicators that are available in all countries.

Third, the nonlinearity in the impact of consumption losses on welfare (due to the concavity of the utility function) is taken into account only by attributing an additional loss to households who experience negative income the year of the shock (with asset losses being "amortized" over time through income losses instead of being entirely subtracted from income the year of the shock). A more sophisticated approach would require integrating the utility impact on the distribution of income losses, which is much more complicated. Moreover, this analysis is based on the utilitarist framework, assuming that there is a utility function that describes individual utility and welfare and that a social utility function can be constructed through the aggregation of individual utility functions. Different frameworks would lead to different outcomes. For instance, a Rawlsian framework would lead to a higher weight given to the poor vs. the non-poor, and probably to a stronger emphasis on the instantaneous income losses described in Section 3.2.

Finally, it is also critical to add here that this framework looks at the economic resilience, but disregards direct human and welfare effects (death, injuries, psychological impacts, etc.), cultural and heritage losses (e.g., the destruction of historical assets), social and political destabilization, and environmental degradation (for instance when disasters affect industrial facilities and create local pollution). The framework proposed here is for economic resilience, not for a broader concept of resilience. Future work will be directed toward these four areas.

Ideally, the various parameters would be estimated through data collection and analysis. If the lack of data means that such an assessment of the resilience indicator is impossible, an alternative is to use an index that compiles multiple proxies for resilience. For instance, the parameter Ψ can be qualitatively estimated from the wealth of the population, the level of financial inclusion, and insurance penetration. The present framework is useful in that case, as it allows organizing the various proxies and makes sure the approach is comprehensive and balanced. As an illustration for such an approach, Table 2 provides a list of the various concepts described in this paper, with relevant parameters to estimate country-level resilience, potential model or measurement methods to quantify resilience, and examples of policies that can improve resilience (and reduce welfare risk) through the different channels.

COMPONENTS OF THE WELFARE DISASTER RISK	PARAMETER(S)	INDICATORS AND/OR MODELS	POLICIES TO REDUCE THE WELFARE DISASTER RISK
Hazard	The probability of occurrence of disasters (p for various events);	Hazard maps for countries can provide this information (with uncertainty) based on historical data; hazard maps can be adjusted based on climate models to investigate future conditions (even larger uncertainty)	Climate change mitigation and local environmental protection
		Alternatively, each country could build a set of "typical events" covering various hazards (e.g., earthquake, storm, etc.) and various intensities (e.g., return periods of one, ten, and 100 years).	
		Alternatively, a simple analysis can classify countries in terms of none, low, medium, and high hazards for the main hazards (storms, flood, earthquake, etc.)	
Exposure	The exposure to possible disasters, represented by the total affected capital (K^a) and the number of affected households (n^a)	If hazard maps are available (at least for the set of "typical disasters"), then asset and population maps can be used to identify the exposure to these hazards.	Land-use planning and risk-sensitive urban plans Information and education campaigns on risk maps
Vulnerability	The vulnerability of the exposed capital V (or equivalently, total asset losses ΔK)	Inventory of building and infrastructure vulnerability and robustness assessment	Building norms, reinforced infrastructure Early warning system and evacuation schemes. Information and education campaigns on risk maps
		Fraction of the population covered by an early warning system and with ability to prepare and evacuate	
Macro-economic resilience (R^{macro})	The interest rate and marginal capital productivity (r);	Macroeconomic data provide this information	Policies to improve the macroeconomic context

	The reconstruction duration in years (N)	For a given event, it can be estimated using sophisticated models, or by experts for a set of "typical disasters", based on the size of the construction sector, the size of the disaster(s) (ΔK), and the ability of the government, firms and households to finance reconstruction (including through insurance programs, foreign aid, and fiscal space), and the access to out-of-the-region resources (e.g., construction equipment) to facilitate reconstruction.	Fiscal space and sovereign risk financing and insurance Firm and household savings, insurance and access to credit Economic openness and agreements with neighbouring regions/countries to share reconstruction resources
	The ripple-effects that amplify (or diminish) instantaneous production losses (α)	This can be expert-based, as no models are available to do a realistic assessment, based on the existence of idle resources, the connection with other regions (to replace missing inputs in supply-chains), and the existence of contingency plans in firms and government.	Infrastructure design standards Incentives for supply-chain risk management Firm insurance schemes
Micro-economic resilience (R^{micro})	The level of income in the country (represented with $u'(c_r)$)	This parameter can be estimated based on GDP per capita, and represent a global distributional weight (the affected country compared with other countries). Assuming that \$1 adds 1 unit of utility in the richest country, then \$1 adds $u'(c_r)$ unit of utility in other countries (with $u'(c_r) > 1$).	Policies that promote economic growth
	The inequality level (represented with $\Delta u'$)	This parameter can be estimated based on inequality within the affected country, and represent the distributional weight attributed to the poor. Assuming that \$1 adds $u'(c_r)$ unit of utility for the non-poor, then \$1 adds $u'(c_r) + \Delta u'$ unit of utility for the poor.	Policies that reduce inequality
	The "poverty bias" of disasters, i.e. the relative exposure of the poor (ω^a), compared with the share of assets owned by the poor (ω).	This parameter can be estimated using the set of typical disasters. Using hazard maps, and asset and population maps that distinguish poor and non-poor (e.g., using poverty maps), then one can estimate the exposure of the poor and the non-poor, and compare the result with the average value of the assets of the poor and the non-poor.	Land-use plans and urbanization plans that prevent the development of low-income housing in risky areas Building norms, reinforced infrastructure. Support for households to improve their housing conditions (especially in slums). Early warning system and evacuation

			schemes. Information and education campaigns on risk maps
	The heterogeneity in direct losses across households (h)	This parameter depends on the hazards (e.g., high winds have often impacts that are less concentrated than floods), but also on the diversification of the economic system (e.g., if households have multiple sources of income, it is more likely than losses will be shared among more households).	Diversification of income within households Diversification of activities at the local and regional level.
	The ability of the households to smooth income shocks over time (Ψ);	This parameter can be estimated using the fraction of the population with access to financial services, insurance systems, or support for access to credit in post-disaster contexts.	Financial inclusion and stability Household insurance programs, especially when they target the poor Facilitated access to credit in post-disaster situation
	The maximum loss of welfare that an household can suffer from (Δw_{max});	This parameter is largely a political choice that describes the value attributed to avoiding leaving households with nothing (for instance based on an acceptable estimate of the "value of a statistical life"). It can also account for the ability of the government to provide emergency services to the affected population (that depends on government resources and access to foreign aid), and the basic safety net that the poorest can access.	Emergency actions (in kind provision of foods, shelter, health care etc.) (the ability to do so will depend on fiscal space and sovereign risk financing and insurance) Basic safety nets, including conditional and unconditional cash transfers
	The amount of risk-sharing in the economy, represented by σ	This parameter can be estimated based on the fraction of the population with access to social protection, subsidized insurance products, and on the ability of the government to provide emergency services to the affected population (that depends on government resources and access to foreign aid)	Emergency actions Subsidized insurance for the poor Safety nets, including conditional and unconditional cash transfers

Table 2: List of concepts, parameters, measurement tools, and policies to reduce the welfare disaster risk.

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6 Appendix A: An extreme case of capital complementarity

One way of investigating these two issues is to assume that there are two categories of capital, K_1 and K_2, that are not substitutable (i.e. the production function is a Leontieff function with decreasing returns):

$$Y = [\mathrm{Min}(\alpha_1 K_1, \alpha_2 K_2)]^\gamma \quad \text{(A1)}$$

K_1 and K_2 could be interpreted as two segments of a road, for instance: if one segment is completely destroyed, the second segment productivity falls to zero, and the total capacity of the road is given by its segment with the lowest capacity.

Total capital is $K = K_1 + K_2$. At the optimum, we have $\alpha_1 K_1 = \alpha_2 K_2$, and:

$$K_i = \left(\frac{\alpha_j}{\alpha_1+\alpha_2}\right) K \tag{A2}$$

(with *j* equal to 2 when *i* is equal to 1, and vice-et-versa). Assuming that capital *K* is distributed optimally across K_1 and K_2, the production function becomes:

$$Y = \left[\frac{\alpha_1\alpha_2}{\alpha_1+\alpha_2} K\right]^{\gamma} \tag{A3}$$

This production function is equivalent to a classical Cobb-Douglas function (assuming that the labor input is fixed and included in the parameters). In fact, one assumption in a production function is that capital can be aggregated into a unique variable *K*, assuming that capital is then optimally distributed across categories of capital (i.e. across sectors, technologies, localization, etc.).

The return on capital is equal to the interest rate plus the depreciation rate:

$$\frac{\partial Y}{\partial K} = i + \delta = r \tag{A4}$$

This relationship gives the optimal amount of capital:

$$\overline{K} = \left(\frac{\gamma A}{i+\delta}\right)^{\frac{1}{1-\gamma}} \tag{A5}$$

Where $A = \left[\frac{\alpha_1\alpha_2}{\alpha_1+\alpha_2}\right]^{\gamma}$.

If only K_i is affected by a disaster, then $K_i < K_j$, and the production is driven by K_i only and becomes:

$$Y = [\alpha_i K_i]^{\gamma} \tag{A6}$$

And the loss in output from a marginal loss of K_i is:

$$\frac{\partial Y}{\partial K_i} = \gamma \alpha_i^{\gamma} K_i^{\gamma-1} \tag{A7}$$

Replacing K_i using Eqs. (A2) and (A5), we get:

$$\frac{\partial Y}{\partial K_i} = \left(\frac{\alpha_1+\alpha_2}{\alpha_2}\right) r \tag{A8}$$

This can be generalized for case with N categories of capital into:

$$\frac{\partial Y}{\partial K_i} = \left(\frac{\sum \alpha_j}{\sum \alpha_j - \alpha_i}\right) r \tag{A9}$$

In that case, the destruction by a disaster of a (marginal) amount ΔK_i of one type of capital would lead to a loss of output equal to:

$$\Delta Y(t_0) = \left(\frac{\sum \alpha_j}{\sum \alpha_j - \alpha_i}\right) r \Delta K_i \qquad \text{(A10)}$$

If α_i is really small, the marginal productivity of capital K_i can be extremely high, much higher than the marginal capital productivity given by Eq. (A4). This case is somewhat extreme because the different categories of capital are assumed non-substitutable, but the qualitative result remain valid with higher substitutability: *considering disaggregated capital categories with imperfect substitutability*[33]*, a disaster would break the assumption that the total amount of capital is optimally distributed across these categories, increasing the marginal productivity of destroyed capital and the value of output losses (and as a result, the marginal productivity of reconstruction).*

7 Appendix B. Quantity and prices in disaster aftermaths

For marginal shocks, impacts can be estimated using pre-disaster prices, i.e. assuming that the shock has a negligible effect on prices. But this assumption is not always valid. Post-disaster price inflation (also referred to as "demand surge") is especially large in the construction sector, which sees final demand soar after a disaster. For instance, Figure B1 shows the large (and persistent) increase in wages for roofers in an area heavily affected by hurricane losses in Florida in 2004.

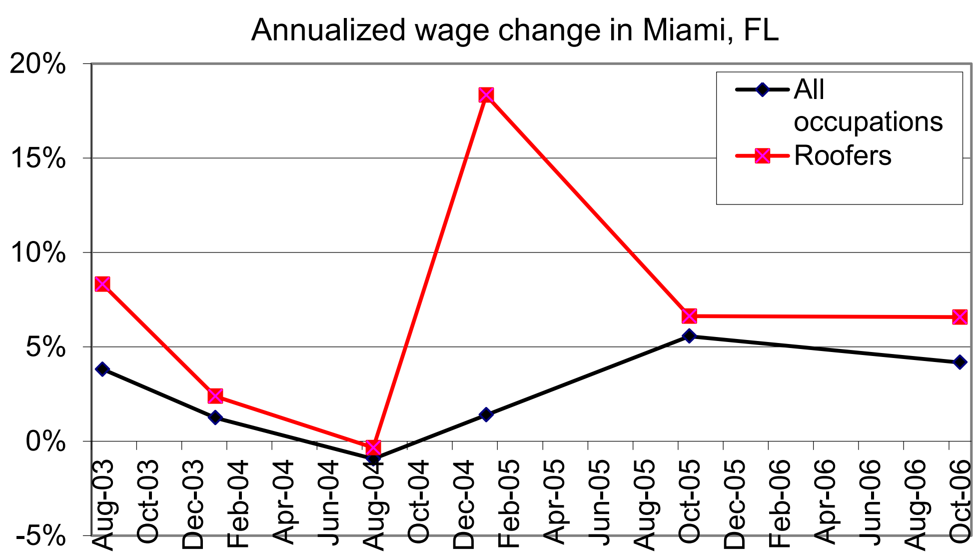

Figure B1: Roofer wages in an area where losses have been significant after the 2004 hurricane season in Florida. Data from the Bureau of Labor Statistics, Occupational Employment Surveys in May 03, Nov 03, May 04, Nov 04, May 05, May 06, May 07.

Figure B2 is a classical quantity-price plot, showing the long-term demand and supply curves for a goods or service aggregated at the macroeconomic level. The green line is the demand curve: it shows how the

[33] The only case where this result does not hold is when the production function is in the form: $Y=f(K_1+K_2+...+K_n)$.

quantity demanded by consumers decreases when the price increases. The blue curve is the pre-disaster (long-term) supply curve: it shows how the quantity produced increases with the price (or, equivalently, the price asked by producers to produce a given quantity). The point A is the intersection of demand and supply and shows the price and quantity that clear the market (at that point, supply equals demand). The economic "surplus" is the area ADE. The consumer surplus is the upper area (AFE) and the producer surplus the bottom area (AFD).

The red line is the short-term supply curve after the disaster: because of damages, production cannot exceed Q_1, and the supply curve becomes vertical at this level (whatever the price consumers are ready to pay, producers cannot produce more than Q_1). If the market clears, the new equilibrium is reached at point B, where the quantity is reduced to Q_1 and the price increases to p_1.

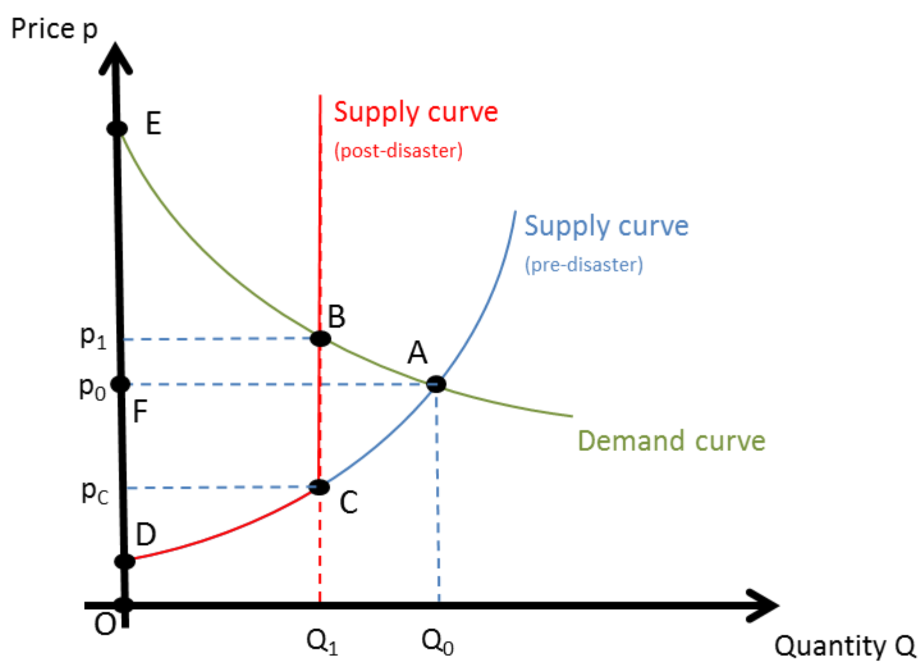

Figure A2. Supply and demand curves in the pre- and post-disaster situations.

In classical economic reasoning, the move from A to B is reducing the pre-disaster surplus ADE to the area BCDE. In other terms, the surplus loss is ABC. But this would be correct only if firms were deciding to reduce production from Q_0 to Q_1 *and to reduce the expenditure needed to produce Q_0*. If firms decided to reduce investment and production capacity from Q_0 to Q1, they would reduce their sales from p_0Q_0 to p_1Q_1, and reduce their production expenses from the area $ODAQ_0$ to the area $ODCQ_1$.

When a disaster hits, however, the sales are reduced from p_0Q_0 to p_1Q_1, but the expenses are not reduced from the area $ODAQ_0$ to the area $ODCQ_1$. This is because firm expenses have three components: intermediate consumptions, capital expenses, and labor. The reduction in intermediate consumptions translates into a loss of output for another firm, so at the macroeconomic level, a reduction in intermediate is not a gain. Reduction in labor expenditures is also a loss for workers, so it should not be counted at the macroeconomic level (unless, workers can find instantaneously another job, which is mostly not the case in disaster contexts). Finally, when a disaster reduces the production capacity from Q_0 to Q_1, it does not do so by reducing capital expenses, but by damaging existing capital. If a firm at a loan to pay for its capital (factory, equipment, etc.), the capital is destroyed but the loan is still there. In other terms, the capital expenditures are not reduced by the disaster.

So to assess the disaster impact on welfare over the short-term, it makes sense to consider the area Q_0ABQ_1 (and not the area ABC as in classical long-term welfare analysis). If the price is unchanged, then the impact can be estimated as $p_0\Delta Q$ (i.e. the loss of output). If the price change is significant, then it is necessary to take it into account, but it is challenging because the shape of the form Q_0ABQ_1 is complex. A linear assumption would simply be: $(p_0 + p_1)\,\Delta Q/2$.

8 Appendix C: Distribution of losses and negative income

Here, we will assume that disaster income losses (relative to pre-disaster income) are distributed according to a Gumbel probability distribution function (a standard distribution for extreme events) across households. The corresponding cumulative distribution function is given by:

$$CDF(l) = e^{-e^{-\frac{l-\mu}{\beta}}} \tag{C1}$$

The parameters μ and β are the location and shape parameters, respectively. At time t, the average household income loss is equal to:[34]

$$\Delta y_p(t) = \overbrace{\left(\frac{1+\alpha}{\mu} r\right)\Delta K}^{\Delta Y(t)} \frac{y_p(t)}{Y^a(t)} \tag{C2}$$

The variable $y_p(t)$ is the income of the poor households, and $Y^a(t)$ is the aggregate income of all affected households. Note that the variables are not the net present value of the flux of consumption and losses, but annual values at time t. With a Gumbel probability distribution function, the mean of the distribution is given by $\mu + \beta\gamma$, where γ is the Euler–Mascheroni constant, approximately equal to 0.5772.

We therefore have:

$$\mu + \beta\gamma = \frac{\Delta Y(t)}{Y^a(t)} y_p(t) \tag{C3}$$

To estimate the parameter β, we use the fact that the median of the distribution is $\mu - \beta\chi$, with $\chi = \ln(\ln(2))$. We now assume that the median is equal to a fraction h of the average. This parameter is a measure of the heterogeneity of asset losses: if h is very small, it means that losses are very heterogeneous.

[34] We keep assuming that losses, income, and assets are linearly related.

The relationships for the mean and median of a Gumbel distribution allows to calculate β and μ as:

$$\beta = \frac{1-h}{\gamma+\chi}\frac{\Delta Y(t)}{Y^a(t)}y_p(t) \quad \text{(C4)}$$

And

$$\mu = \frac{h\gamma+\chi}{\gamma+\chi}\frac{\Delta Y(t)}{Y^a(t)}y_p(t) \quad \text{(C5)}$$

The fraction of households for which losses exceeds annual consumption is then given by:

$$X = 1 - CDF\left(y_p(t)\right) = 1 - e^{-e^{-\frac{y_p(t)-\mu}{\beta}}} \quad \text{(C6)}$$

Replacing β and μ, we have:

$$X = 1 - e^{-e^{\frac{1}{1-h}\left(-(\gamma+\chi)\frac{Y^a(t)}{\Delta Y(t)}+h\gamma+\chi\right)}} \quad \text{(C7)}$$

In this equation, the income of the poor ($y_p(t)$) does not affect the ratio X. As a result, this equation can be used in the same way to the non-poor, and X is the fraction of all households for which initial income losses exceed annual income.

Note that what we look at is the income loss due to asset losses, but we do not subtract the whole asset loss the year of the shock (otherwise, a large proportion of affected households experience negative income the year of the shock). This “loss amortization” is more relevant to assess welfare losses.
With our assumptions, we have:

$$\frac{\Delta Y(t)}{Y^a(t)} = \frac{\left(\frac{1+\alpha}{\mu}r\right)\Delta K}{\left(\frac{r}{\mu}\right)K^a} = (1+\alpha)\frac{\Delta K}{K^a} \quad \text{(C8)}$$

This framework can easily be connected to the classical risk framework combining hazard, exposure, and vulnerability. Indeed, the direct losses, ΔK, can be classically expressed as a combination of exposure and vulnerability. For a given event, we have

$$\Delta K = K^a V \quad \text{(C9)}$$

So finally, we have:

$$X = \Theta((1+\alpha)V\,, h) \quad \text{(C10)}$$

With

$$\Theta(x,h) = \left(1 - e^{-e^{\frac{1}{1-h}\left(-(\gamma+\chi)\frac{1}{x}+h\gamma+\chi\right)}}\right) \quad \text{(C11)}$$