**Are losses from natural disasters more than just asset losses?**

The role of capital aggregation, sector interactions, and investment behaviors

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**Abstract**

The welfare impact of a natural disaster depends on its effect on consumption, not only on the direct asset and human losses that are usually estimated and reported after disasters. This paper proposes a framework to assess disaster-related consumption losses, starting from an estimate of the asset losses. Using a traditional production function would lead to a systematic underestimation of disaster output losses, and immediate output losses after a disaster reduces the capital stock are better estimated by using the average – not the marginal – productivity of capital. As a result, the net present value of disaster-caused consumption losses decreases when the reconstruction is accelerated. With usual parameters, discounted consumption losses are only 10 percent larger than asset losses if reconstruction is completed in one year, compared with 80 percent if reconstruction takes 10 years. Another interesting result is that, for disasters of similar magnitude, consumption losses are expected to be lower where the productivity of capital is higher, such as in capital-scarce developing countries. This mechanism may partly compensate for the many other factors that make poor countries and poor people more vulnerable to disasters. Finally, the paper explores the role of investment behavior in the presence of risk, and finds that beyond avoided losses, disaster risk management can generate additional benefits through higher investment and more capital accumulation. This “second benefit” of risk reduction can be between 20 and 200 percent of avoided losses, depending on risk aversion and capital productivity. The economic cost of natural disasters is not limited to their impact when they actually occur: the possibility of a disaster already reduces economic output.

# Introduction

What is the economic cost of a natural disaster? Events such as floods or earthquakes destroy assets such as roads, plants, or office space, thus leading to losses of economic production over the following months to years or decades. Since the economic value of an asset is the net present value of its expected future production, the output loss caused by a disaster is simply equal to the value of the lost assets. So while summing asset and output (or income) losses would be double counting,[[1]](#footnote-1) the cost of a natural disaster can be assessed from either. However, the most natural way of measuring the value of damaged assets, through their construction cost or pre-disaster market, may be inaccurate if the economic conditions when the assets were built differ from the conditions after the disaster hit. This paper explores how economic theory can help practitioners assess production losses from natural disasters, and thus their cost.

We focus on the role of using economic aggregates, and in particular an aggregated capital stock, in the analysis of the macroeconomic impact of natural disaster. This question is an old economic question. Stiglitz (1974) summarizes the issue, assuming that we are more interested in practical than theoretical question:

*“From a practical point of view, economists are always dealing with aggregates: one person's labor is aggregated with another, one piece of land is aggregated with another, one kind of steel is aggregated with another, even though they all have different properties. The condition under which these aggregates can be formed, that is, under which the aggregates act as if they were homogeneous factors of production, are very restrictive; nonetheless, I believe that, under most circumstances and for most problems, the errors introduced as a consequence of aggregation of the kind involved in standard macro- analysis are not too important; nonetheless, we must always be on our guard for situations in which this is not true. The question is, Do the problems associated with the accumulation of capital in growth processes represent one area in which properly formulated aggregates (e.g., using chain indices) are likely to lead to serious error? This, I suggest, remains a moot question.”*

Here, we suggest that the analysis of natural disasters may be one of these cases for which Stiglitz advised us to be on guard, that is one case where aggregation can lead to errors that are too great to ignore. We find that using a traditional production function would lead to a systematic underestimation of disaster output losses, and that immediate output losses after a disaster reduces the capital stock are better estimated by using the average – not the marginal – productivity of capital.

The proposed framework concludes that the net present value of disaster-caused consumption losses decreases when the reconstruction is accelerated. Discounted consumption losses are only 10 percent larger than asset losses if reconstruction is completed in one year, compared with 80 percent if reconstruction takes 10 years. After a disaster there is an urgency to redirect resources away from new investments to concentrate them on repairs and reconstruction. This fact is consistent with the higher marginal productivity of reconstructed capital (compared to investment in new assets) that is found in the framework proposed here.

Another interesting result is that, for disasters of similar magnitude, consumption losses are expected to be lower where the productivity of capital is higher, such as capital-scarce developing countries. This mechanism may partly compensate for the many factors that make poor countries and poor people more vulnerable to disasters, such as the lower quality of their assets, their lack of access to insurance and credit, and their low level of pre-disaster consumption (Hallegatte et al., 2016).

Finally, the paper explores the role of investment behavior in the presence of risk, and finds that beyond avoided losses, disaster risk management can generate additional benefits through higher investment and more capital accumulation. This is the “second benefit” discussed in the Triple Dividend Report (ODI and World Bank, 2015). With typical behavior parameters, the total gains in expected consumption are found between 20 and 200 percent larger than only avoided losses, depending on risk aversion and capital productivity. Thus the economic cost of natural disasters is not limited to their impact when they actually happen, the mere probability of serious events to happen reduces economic output.

# Output losses with a classical production function

Production functions relate the inputs and the outputs in the production process. Classically, output can be represented as

Where L denotes the amount of labor, K the amount of capital, and Y the output. In this framework, the damage that natural disasters – such as floods, storms, earthquakes – impose on assets can be modeled as an instantaneous decrease in the stock of productive capital (), where is the value of the asset losses, measured as the repair or replacement cost at pre-disaster prices (this is the common metrics used to measure disaster economic losses).

For small shocks, the impact on production can be estimated using the marginal productivity of capital. Denoting the marginal productivity of capital:

(1)

If there is no reconstruction, the net present value of the constant output losses discounted at an unchanged rate equals the pre-disaster replacement value of lost assets:

(2)

In a more realistic setting, however, this method to assess output losses may lead to significant underestimation. One issue is that asset losses may be too large to be considered marginal. To assess non-marginal shocks on the capital stock, one can use the full production function, and decrease the amount of capital from K0 to K0 – ΔK. In that case, output losses are larger than in the idealized (marginal) framework and Equation (1) is replaced by:

(3)

This factor alone would make the net present value of the output losses larger than the value of the damages to asset expressed with pre disaster prices.[[2]](#footnote-2)

# Disasters affect the capital structure, not only the capital quantity

Equation (3) assumes that the destructions from the disaster affect only the least productive assets, or that capital consists only in one homogenous commodity that can be instantaneously reallocated toward its more productive usage. However, this assumption is unlikely to be valid after a disaster, because assets such as roads or offices cannot be transformed into other assets such as bridges or factories at no cost and instantaneously.

## Accounting for imperfect capital reallocation

Let us use a simple example with an economy where capital consists only of roads that produce “transport services”. Roads are built starting from the most productive, that is the one used by the most people, to less productive ones, used by fewer people. At a given point in time, some roads have a high productivity, and some roads have a low productivity. Only the least productive road has the same productivity as the aggregated capital stock, i.e. the marginal productivity of capital. At equilibrium, and assuming that all roads cost the same, the construction cost of the least productivity road is equal to the discounted value of its production. The other roads have a higher productivity, and the value of their production is larger than their construction cost.

If a shock destroys the least productive road, the instantaneous loss of production (transportation service) is equal to the value of the destroyed road multiplied by the marginal productivity of capital. In that case, the net present value of the output loss is simply equal to the value of the road, as in equation (2).

But to assume that the destruction of *any* road will cause a discounted output loss equal to the construction value of the road, we have to assume that roads can be instantaneously reallocated to their most productive use, i.e. that roads can be moved where it they are the most useful, which is of course impossible. The production loss associated with the destruction of an arbitrary road segment is equal the construction cost of a segment times to the productivity of that particular segment, which is higher than the marginal productivity of aggregated capital. This example shows that the production loss can be higher than the marginal productivity of capital, and the net present value of the lost production can be larger than the construction or replacement value of the road. The replacement value of lost assets provides an underestimation of the net present value of the loss in output.

If the disaster affects more flexible forms of capital, then capital reallocation is possible. The owner of a damaged car can for instance buy the least productive undamaged car to its owner. However, this reallocation is (1) not instantaneous (it takes time for all of transactions to take place); (2) not costless (there are transaction and adjustment costs in capital reallocation); (3) not complete (some capital, like the roads in the previous example, cannot be reallocated, for technical, financial, institutional or behavioral reasons).

This issue links to the possibility to describe the capital stock with a single number in an aggregate production function. The question was core to the Cambridge capital theory controversy and the limits of the one-commodity model (Cohen and Harcourt, 2003), and to Robinson's (1974) critics on the problem of path dependence. Indeed, the capital stock can be represented unambiguously through a single number only if this capital stock is the result of a process of optimal capital accumulation, or if capital can be reallocated instantaneously and at no cost toward its optimal use. Only the assumption of optimal capital allocation allows to remove relative prices and interest rate from the valuation of the capital stock and make it possible to measure capital with a single variable (Cohen, 1989).

Even if capital was allocated optimally during its progressive accumulation, a natural disaster destroys random fraction of this capital, and there are obvious limits to the capital reallocation in a disaster aftermath. In what follows, we investigate the impact of capital losses on aggregate output in a model with explicit categories of capital that cannot be relocated across categories. We then use a different approach, using a model with a single stock of productive capital, where two dimensions (total capital and fraction of capital destroyed) are used to describe the stock of capital and the production process.

### 2.1.1. Modeling disaster impact on output with layers of capital

Let us first assume that the capital is the aggregation of many “layers” of capital:

Layers can be broad (homes, vehicle, manufacturing equipment, etc.) or narrow (a road going from A to B, the cars in the city C, the houses of the neighborhood D, etc.). Each capital layer *i* has a uniform productivity, such that:

There is also a maximum amount of capital in each capital layer: . For instance, once all roads in a neighborhood are built, building more roads will not produce more mobility. This can be seen as an extreme version of decreasing returns within categories: the marginal productivity is constant until a given threshold, and then drops to zero when all opportunities for investment within that layer of capital are exhausted.

We rank the layers of capital so that their productivities are decreasing:

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The production function is given by:

If the aggregated capital stock K is allocated optimally, investment goes first to the highest-productivity layer of capital until all potential is exhausted, then moves to the second-best layer of capital, and so on. Only the last layer used may have unused potential in the sense that:

The production function becomes:

And the marginal productivity of aggregated capital is given by the productivity of the least productive used layer of capital:

The production function meets all of the classical properties. In particular, the marginal productivity of capital is decreasing with *K*, that is the production function exhibits decreasing returns.

With such a production function, a destruction of capital can lead to a loss of production given by the marginal productivity of capital , but only if the destruction occurs in the last layer of capital (or if capital could be reallocated from the lower- to the higher-productivity capital layers).

A more plausible case is if capital destruction is distributed uniformly over the layers of capital, that is for all *i*:

Assuming capital reallocation is not possible across capital layers, the impact on production is:

In other words, the productivity of destroyed capital, equals , the average productivity of capital – not the marginal productivity of capital. In particular, output losses are higher than the construction value of damaged assets.

Importantly, this larger impact of capital losses does not require that reallocation of capital is entirely impossible – the result holds if reallocation of capital is possible within layers (a car or a house can be reallocated to its most efficient use), but not across layers (a house cannot replace a damaged road).

### 2.1.2. Modeling disaster impacts with categories of fully substitutable capital

Consider now a more generic model, in which capital still consists of a sum of different types of capital:

And that each capital category produces output with the same production function:

Where f has all the classical properties, and in particular and . The total production is simply the sum of the output of all categories:

If capital K is allocated optimally across the capital categories, there is one such that for all i:

So that all are equal and thus equal to K/N. Under the assumption of perfect capital allocation, we can describe the production process with the following aggregate production function:

In this case, the marginal productivity of aggregate capital is given by:

And the second derivative of production is:

So this aggregate production function meets the classical conditions of a production function.

Assume now that a shock destroys a non-marginal quantity of capital. If capital remains optimally allocated, then the impact can be approximated by:

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If capital losses occur only in one (say, the first) category of capital, and assuming perfect reallocation within categories but not across categories, the result is:

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So that:

For marginal shocks, if is negligible, representing capital and production as aggregates only does not lead to a significant underestimation of capital losses. But if losses are large or concentrated on a few sectors, if the numbers of layers across which capital cannot be reallocated is large, (or if the second derivative is large in absolute value), the difference can be substantial. In this case, representing the production process with an aggregate capital stock would lead to underestimate the effect of asset losses on production. And this aggregation error increases with the size and concentration of the shock: as the disaster becomes more serious, or if losses are concentrated spatially or sectorally, then the aggregated production function leads to a larger underestimation of the losses.

In such a model, whether a shock is small or marginal cannot be decided by comparing the total amount of losses to the total amount of capital . One has to consider each category of capital (within the N categories) and compare the losses within that category to the amount of capital in that category[[3]](#footnote-3). For instance, if a disaster destroys an entire category of capital total capital losses are , and output losses equal :

Here again, the loss in output is equal to the loss in asset multiplied by the average – not the marginal – productivity of capital, even if the total amount of capital destroyed is very small. In particular, if the economy is partitioned in a very large set of categories *N*, and disasters tend to destroy entire categories of capital at once (for instance a bridge is usable or not), then output losses depend on the average productivity of capital. (On the other hand, if categories are only partially damaged, then losses are lower – if a bridge is only partially damages and can accommodate 50% of peak traffic, it is likely that the service it produces is reduced by less than 50%.)

### 2.1.3. Modeling aggregate capital with two variables

Two distinct representations of the capital as the aggregation of many categories of capital lead us to represent the impact of a disaster on economic output using the average instead of the marginal productivity of capital.

Another way to represent these mechanisms keeping track of a single stock of capital is to describe this stock with two variables instead of one. The first variable is total amount of capital in the absence of disaster damages and the second variable is the amount of damaged capital . In the absence of damages, the output is given by the usual production function. When a fraction of the capital is damaged, output is reduced proportionally to the loss in capital: if 10% of the capital stock is lost, then 10% of the instantaneous output is lost:

(4)

In this model, asset losses add to destroyed capital, instead of reducing constructed capital K. With these assumptions, lost capital has a productivity equal to the average productivity of the capital in the economy, and

(5)

With equal to the average productivity of capital *F(L,K)/K*. Assuming no reconstruction, output reduction is permanent, and the net present value of output losses is:

(6)

With these assumptions, the net present value of the loss in output is larger than the value of lost assets expressed as replacement value at pre-disaster prices (since average productivity is higher than marginal productivity). Assuming a Cobb-Douglas production function and using a share of capital income of 1/3, as is observed in most economies, discounted output losses are three times larger than what an estimation with a traditional production function would suggest.

More generally, traditional production functions, such as Cobb-Douglas depending on labor and capital, are good representations of long-term factor allocations, when capital reallocation and technology adjustments to substitute capital and labor are possible. Over the short term, factor allocation is less flexible. This can be represented with a Leontief-style production function, in which either labor or capital can be the binding constraint. Denoting the part of labor that becomes unusable after the disaster:

## Interactions between damaged and undamaged assets

The previous section suggests that the productivity of the lost capital may be larger than the marginal productivity of capital, but still assumed that the assets that have not been directly affected by the disaster can continue producing with an unchanged productivity.

But we also need to take into account the spill-over effects of asset losses: when assets are imperfectly substitutable, the loss of one asset affects the productivity of other assets. 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 disaster can also reveal unable to produce at the pre-event level because of indirect impacts. There are two propagation mechanisms.

### 2.2.1. Downstream propagation

The first one is a downstream propagation, when one producer cannot produce because one input in the production process is missing. For instance, most economic activity cannot take place during power outage, because electricity is an essential (and often non-substitutable) input in the production process.

#### 2.2.1.1. Anecdotal evidence

(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. In most cases, the loss in the housing services produced by a house is not due to an impact on the house itself, but to impacts to complementary assets (e.g., water pipes).

(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 due to a disaster depend not only on interactions across sectors but also on interactions across firms (Henriet et al., 2012). Business perturbations may indeed also arise from production bottlenecks through supply-chains of suppliers and producers.[[4]](#footnote-4) Modern economies, with global supply chains, limited number of suppliers and small stocks, may be more vulnerable to natural disasters than traditional, close economies. The impact of disasters on supply chains are illustrated by the large 2011 floods in Thailand. Car manufacturing in Thailand dropped by 50% to 80%, and Toyota was the company hit the hardest in terms of production loss, even though none of its plants got inundated: A critical supplier in the manufacturers’ supply chains was affected by the floods (Haraguchi & Lall, 2015). Similarly, the global production of hard drive disks (HDD) decreased by 30% in the 6 months after the floods, causing a price spike between 50% and 100% (Haraguchi & Lall, 2015; Japanese Ministry of Economy, 2011). This production loss was not only caused by the disruption of production facilities in Thailand, but also further HDD manufacturers outside of Thailand were affected by missing parts from suppliers in flooded areas (Wai & Wongsurawat, 2013).

#### 2.2.1.2. Illustrative modeling

In theoretical terms, these spill-overs across sectors can also 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. 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. (On the other hand, if different types of capital are substitutable, the destruction of one type of capital can be compensated partially with the utilization of another type of capital. For instance one road from A to B can become more productive, that is be used by more passengers, if an alternative route from A to B is destroyed.)

One extreme example is the case of a road that is built out of a series of segments between two points: 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 construction value of that segment alone, 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 disregarded if one assumes that the capital stock is always (both before and after an event) optimally allocated (in that case, road segments can be moved to their most efficient uses).

This problem can be illustrated by replacing the classical production function f(L,K) by a function with two types of capital f(L,K1,K2). If there are decreasing returns in K1 and K2, the impact of a given loss K=K1+K2 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.

These two issues can be illustrated with a simple example. Assume that there are two categories of capital, *K1* and *K2*, that are not substitutable. The production function is a nested Cobb-Douglas between capital services and labor, and capital services are produced using the two capital categories, through a Leontieff function:

*K1* and *K2* could be interpreted as two segments of a road with different construction costs, 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. If one segment is damaged so that only half of the traffic can go through, then the second segment also sees half of the traffic and its productivity is also halved.

Total capital is . At the optimum, ve. If we assume that capital K is always distributed optimally across *K1* and *K2*, the production function becomes:

This production function is a classical Cobb-Douglas function, and it can be used to estimate changes in production resulting from investments or divestment, provided that the capital is optimally distributed across categories of capital (i.e. across sectors, technologies, localization, etc.), at the marginal productivity of aggregate capital:

If a disaster hits this economy and destroys capital K1 and K2 proportionally, or if the residual capital in the two categories can be reallocated, then the immediate loss of output will be given by the product of the marginal productivity of capital by the value of the damages, and the net present value of capital losses will be equal to the value of the damages, as expected.

But if only one category of capital is affected – say *K1* – then , and if there are no possible reallocation of capital[[5]](#footnote-5), then the production becomes driven by *Ki* over the short term, and the loss in output from a marginal loss of *K1* is:

Replacing *Ki* with and generalizing to n categories of capital, we get:

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

If is small, the net present value of output losses can be much larger than . This case is 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, 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).

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 on total output can be very large (Rose et al., 2007). However, many studies (e.g., Rose and Wei, 2013) find that there is always some substitutability among capital types, and the illustration presented here is an extreme case.

### 2.2.2. Upstream propagation

Across-sector propagations also occur upstream, when a sector that cannot produce reduces its demand to other sectors. (Hanlon, 2014) show that a shock on cotton price caused by the US Civil War had consequences beyond the textile sector. He identifies a demand-related impact: the lower production in the textile sector reduced demand for goods such as machinery and metal produces.

The framework used in Acemoglu et al (2012) allows investigating these propagation effects. Let us assume that the production technology in sector *i* is described by a Cobb-Douglas function:

Where is the capital stock in sector *i,* α ∈ (0 1) is the share of capital income, and is the amount of commodity j used in the production of good i, and represent the share of different intermediate consumption in the production process.

Acemoglu et al (2012) show that with Cobb-Douglas functions, there are no propagations of a productivity shock downstream, because price and quantity effects cancels out. (This result contrasts with our results with Leontieff function, showing that substitutability in the production system is a key factor for downstream propagation). With Cobb-Douglas functions, the only propagations are upstream, through demand, because a sector with lower production will demand less to other sectors, thereby reducing total output.

Assume now that a disaster reduced each sector’s capital by a fraction , the production function becomes:

Acemoglu et al (2012) show the output in the competitive equilibrium is given by:

Where d is the vector of and v is the sale vector:

Where is the pre-disaster competitive equilibrium price of good i.

If a sector that represents 2% of the total sales in the economy loses 10% of its production, the loss in output is 0.2%. Here, the relationship between production and capital losses are given by the Cobb-Douglas function, so that the loss of consumption is worth a fraction of pre-disaster capital – the losses depend on marginal productivity, like in section 2.1.2, because it is implicitly assumed that reallocation is possible at no cost and immediately within each sector i..

Note that v is the sale vector, not the value added vector. It gives more importance to sectors with large intermediate consumption (since intermediate consumption is the wedge between value added and sales). This is a model where propagations are only going upstream – not downstream – in supply chain: it makes sectors with large intermediate consumption more important in reducing aggregate demand in the aftermath of a shock. But it does not make the sectors that produce essential goods – such as electricity – particularly important.

## Externalities

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]](#footnote-6)

One example is the health care system in New Orleans. Beyond the immediate economic value of the service it provides, 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, lost assets () should be valued taking into account externalities. Below, we explore two particular cases: the stimulus effect of reconstruction; and productivity spill-overs from reconstruction.

### 2.3.1. The stimulus effect

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, the economy in Florida was depressed and only 50% of the construction workers were employed (West and Lenze, 1994) when Hurricane Andrew made landfall on south Florida,. 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).

### 2.3.2. Productivity spill-overs

Disasters damage old and low-quality capital, and the reconstruction may allow to “build back better” and to reach an end point that superior in some aspects to the pre-disaster situation. For instance, an earthquake may destroy old, low-quality, buildings, making it possible to rebuild with improved building norms (and higher energy efficiency leading to better comfort and lower energy bills); this possibility has been mentioned for the Christchurch earthquake in New Zealand in 2011. And Hornbeck and Keniston (2014) show that the Great Fire in Boston in 1872 led to a large increase in land values, suggesting that reconstruction created positive local externalities that were difficult to capture through normal building turn-over. More general exploration of this effect, hereafter referred to as the “productivity effect” (closely linked to the “Schumpeterian creative destruction effect”), can be found in Albala‐Bertrand (1993), Stewart and Fitzgerald (2001), Okuyama (2003) and Benson and Clay (2004).

When a natural disaster damages productive capital (e.g., production plants, houses, bridges), the destroyed capital can be replaced using the most recent technologies, which have higher productivities. Capital losses can, therefore, be compensated by a higher productivity of the economy in the event aftermath, with associated welfare benefits that could compensate for the disaster’s direct consequences. This process, if present, could increase the pace of technical change and accelerate economic growth, and could therefore represent a positive consequence of disasters. This effect is often cited to explain why some studies find a positive impact of disasters (Skidmore and Toya, 2002, 2007). However, the productivity effect is probably not fully effective, for several reasons. First, when a disaster occurs, producers have to restore their production as soon as possible. This is especially true for small businesses, which cannot afford long production interruptions (see Kroll et al., 1991; Tierney, 1997), and in poor countries, in which people have no mean of subsistence while production is interrupted. Second, even when destructions are quite extensive, they are never complete. Some part of the capital can, in most cases, still be used, or repaired at lower costs than replacement cost. In such a situation, it is possible to save a part of the capital if, and only if, the production system is reconstructed identical to what it was before the disaster. This technological “inheritance” acts as a major constraint to prevent a reconstruction based on the most recent technologies and needs, especially in the infrastructure sector. This effect is investigated in Hallegatte and Dumas (2009) using a simple economic model with embodied technical change. In this framework, disasters are found to influence the production level but cannot influence the economic growth rate, in the same way than the saving ratio in a Solow growth model. Depending on how reconstruction is carried out (with more or less improvement in technologies and capital), moreover, accounting for the productivity effect can either decrease or increase disaster costs, but this effect is never able to turn disasters into positive events.

# Reconstruction dynamics and consumption impacts

In the previous section, it was assumed that the output losses were permanent, i.e. that there is no investment or reconstruction taking place. In practice, of course, damaged assets are replaced or repaired, often as fast as possible. And if the lost capital has a productivity that is higher than the pre-disaster marginal productivity of capital, the rationale to reconstruct and repair is stronger than the pre-disaster rationale to invest, possibly leading to higher investments. This section investigates this dynamics.

## Modelling the reconstruction phase

Consider the production function proposed in section 2.1.3, where capital is described by two variables; total amount of capital, and amount of capital destroyed. In this model, investment needs to be described by two variables too: investment towards reconstruction of damaged capital (; and the investment into new capital, which is not linked to reconstruction (:

The marginal return on expanding the total capital stock is while the marginal return on reconstruction is . With decreasing return, marginal productivity is lower than average productivity of capital, and the return on is lower than the return on

In this theoretical setting, with perfect capital markets, all post-disaster investments should be dedicated toward the reconstruction instead of damages. For instance, construction of any new house would be postponed to focus efforts toward rebuilding and repairing damaged houses. Similarly, construction of new roads and bridges should be delayed to focus on repairing damaged roads and bridges.

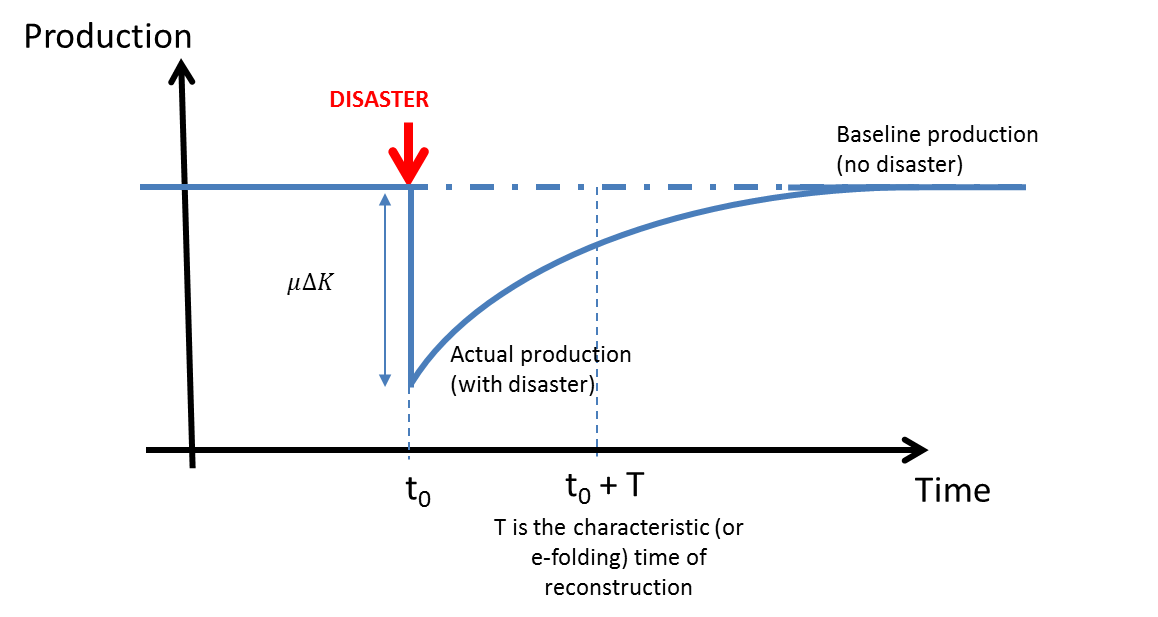
If that was the case, if output could be entirely directly toward reconstruction, damages from disasters would be repaired extremely rapidly. Damages from hurricane Katrina represented less than one month of US investments, so the return to the pre-disaster situation could happened in a matter of months.

But investment in reconstruction is limited by financial and technical constraints. First, the people who lost their assets may not have access to savings or borrowing to pay for reconstruction and repair, and may not be insured, so that they cannot make corresponding investments in spite of their large returns. Second, the economic sectors that are involved in the reconstruction have limited production capacity. For instance, the construction sector usually struggles to cope with the surge in demand seen after disasters, which leads to rationing and increased prices (See Annex). These constraints mean that cannot usually represent more than a limited share of total investment (and total output), leading to reconstruction periods that are much longer than what the amount of losses could suggest.

The length of the reconstruction period depends 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).[[7]](#footnote-8)

## Consequence on consumption

Assuming that output losses are reduced to zero exponentially with a characteristic time T, output losses after are given by:[[8]](#footnote-9)



**Figure 3: Simplified representation of the return to “initial state” after a disaster. This figure assumes a stable (no-growth) baseline.**

With discounting at a rate , the net present value of output losses is:

%% maybe include the increase in reconstruction costs with demand surge – see annex

Consider first a case where 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, and T is equal to zero). In this limit case, there is no output loss since all asset damages are instantaneously repaired. 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 () is simply equal to the reconstruction cost. With unchanged prices, this is equal to the pre-disaster value of damaged assets . (If the prices of goods and services needed for the reconstruction change, as discussed in Annex A, then the reduction in consumption can be larger than the initial assessment of asset losses, a mechanism known as “demand surge” in the insurance industry.)

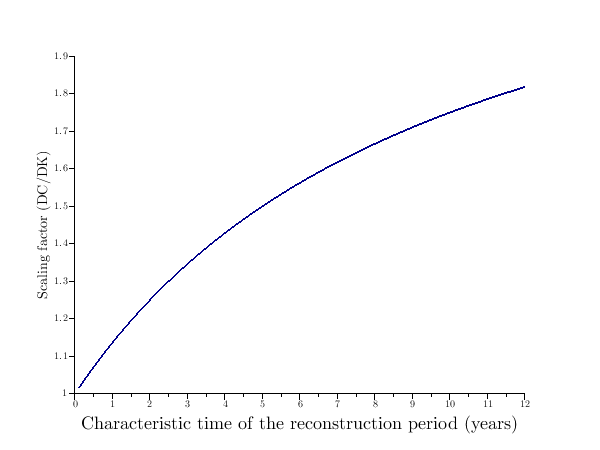
Consider now another case with no reconstruction, in which output losses are permanent and all losses in output are absorbed by a reduction in consumption (but no share of income is used for reconstruction). In that case, consumption losses are equal to output losses (with no reconstruction), and T is equal to infinity. The loss in consumption at is thus equal to , and the net present value (discounted at the rate ) of consumption losses is , as in the previous section. Consumption losses and welfare losses are thus larger than the value of lost assets in a no-reconstruction case.

In the instantaneous reconstruction scenario, consumption losses are equal to the share of consumption needed to repair and rebuild, i.e. to asset losses . In the no-reconstruction scenario, consumption losses are equal to output losses , i.e. larger than direct losses .[[9]](#footnote-10) As a result, consumption (and welfare) losses are magnified when reconstruction is delayed or slowed down. And in all realistic scenarios where reconstruction takes some time (from months for small events to years for large-scale disasters), consumption 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.

The duration of the reconstruction phase determines the welfare cost of natural disasters. The net present value of consumption losses is equal to:

This result depends crucially on the fact that the productivity of destroyed capital is equal to the average pre-disaster productivity of capital. If the productivity of the lost capital was assumed equal to the marginal productivity of capital, i.e. if is replaced by in the equation, then the loss of consumption is simply equal to the loss of capital and is thus independent of the reconstruction duration. There would be no urgency in reconstructing, and accelerating the reconstruction process would not bring any benefit. With the framework proposed here, consumption losses are increasing with the duration of the reconstruction period, a finding that is consistent with the urgency to reconstruct that is easily observable after a disaster.

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**Figure 4: The scaling factor between consumption and asset losses () as a function of the reconstruction duration (defined as the time needed to repair 95% of the losses).**

A corollary of this result is that the consumption (and welfare) impact of natural disasters can be reduced by accelerating reconstruction, for instance by removing some of the financial or technical constraints discussed earlier. Higher penetration of market insurance or better access to borrowing can make reconstruction easier for all economic actors. Higher trade openness helps bring the equipment and materials needed for the reconstruction. Higher openness to workers also helps accelerate reconstruction and reduce the reconstruction cost. For instance, using classical calibration for parameters, reducing a reconstruction period from 5 to 2 years reduces consumption losses by 20 percent (Figure 4).

The framework also suggests that the relative impact on consumption of a disaster is smaller in developing countries than in developed countries. Express annual consumption as the product of propensity to consume (1-s), average capital productivity, and aggregate capital (. Then, the ratio of the net present value of consumption losses to the annual consumption is:

If a disaster destroys 15% of the capital in an economy, the relative loss in consumption decreases with : it tends to infinity for , and decreases to zero as tends to the infinity. Since the average productivity of capital is expected to decrease as countries develop and accumulate capital (Lucas, 1990), rich countries will tend to suffer larger relative consumption losses than poor countries with higher productivity of capital. Where capital has a higher productivity, replacing destroyed capital requires a lower share of consumption.

This counter-intuitive result has a major consequence for resilience and the welfare impacts of disasters. Indeed, this effect contribute to the resilience of poor countries (compared with higher income ones): low-income countries can reconstruct without giving up a large share of their consumption, because the amount at stake are lower, even relative to their income. This factor partly rebalances the many other factors that make poor countries and poor people more vulnerable to natural disaster, such as the higher vulnerability of their capital stock (leading to higher ) and the high impact on welfare of the same relative loss in consumption (for a full analysis of the multiple determinants of resilience, see Hallegatte et al., 2016).

# Ex ante effect of risk on investment and development

In situations where there is a trade-off between reducing exposure to natural hazards and improving productivity or economic growth, improved risk management and more resilient development can mitigate this trade-off and accelerate growth (Hallegatte 2014).

Indeed, both actual and perceived risk change investment behaviors, and thus wealth creation. Taking into account the prospective consequences of shocks, households may manage risk exposure by selecting low-risk, low-return asset and activity portfolios that reduce the risk of greater suffering but limit growth potential (Carter and Barrett, 2006; Dercon, 2005; Rosenzweig and Stark, 1989). The prospected of future capital losses due to natural disasters may discourage adoption of new technologies and decrease incentives to invest in productive capital accumulation.

An illustration of this effect is provided in an agricultural context in Zimbabwe by (Elbers et al., 2007). They find that farmers exposed to risk own on average half as much capital as farmers who are not exposed. Ex-ante investment reductions account for two-thirds of the difference (the rest is due to the losses due to shocks). In that case, therefore, most the welfare impact of risk is through reduced investments, not through the damages and losses when the hazard does materialize into an actual event.

In the following, we estimate the importance of this effect with a simple model. A representative agent can rent capital for one year at an exogenous rate r to produce an output. It is assumed that capital is fully flexible and can be reallocated after one year. There is a probability p that a disaster occurs, and in that case a fraction v of capital is lost. (For simplicity we assume that the capital produces its full output before it is possibly lost, like it the shock could only happen at the end of the year. But adding the possibility of output losses depending on the timing of the shock would not change results significantly because output losses are in that case much smaller than capital losses.) Consumption is given by:

if no disaster occurs (probability 1-p)

if a disaster occurs (probability p)

Assume that a fraction of losses are insured at the fair price :

if no disaster occurs (probability 1-p)

if a disaster occurs (probability p)

The representative agent has a utility function with constant relative risk aversion:

Assume that the agent maximizes his or her expected utility. In this model, natural risks act like an increase in the cost of capital r, and therefore reduces the optimal level of investment. And if insurance is incomplete and in the presence of risk aversion, the agent will further reduce investment, K.[[10]](#footnote-11) In these cases, with or without insurance and risk aversion, risk reduces consumption even when a disaster does not occur, and avoided losses are an imperfect measure of the benefit from risk reduction investments.

This model is extremely simple and its behavior is well understood: when an intervention reduces the probability of occurrence of the disaster, investment increases and the amount of capital is higher, leading to higher expected consumption (and slightly higher capital losses compared to a case with fixed capital). This effect is amplified in the presence of risk aversion, if there is not full insurance. The question is whether this effect will make a significant difference in the assessment of disaster risk reduction.

To investigate this question, we turn toward numerical simulations. Parameters are set at standards values: risk aversion is between 0 and 1.5; interest rate r is between 4 and 12 percent; is 0.3; and v is between 12.5% and 50%.

Each panel in Figure X shows how expected consumption depends on the probability of occurrence of a disaster, in three cases: the case with full insurance or no risk aversion (red), and two cases with no insurance and with risk aversion (green and blue), calibrated so that expected consumption equals 100 when the probability of occurrence is 10 percent. As a reference, the dashed line shows the estimate if the amount of capital K is fixed to its optimal value with the initial disaster probability, so that only avoided capital losses are accounted for. Each panel uses a different value for r.

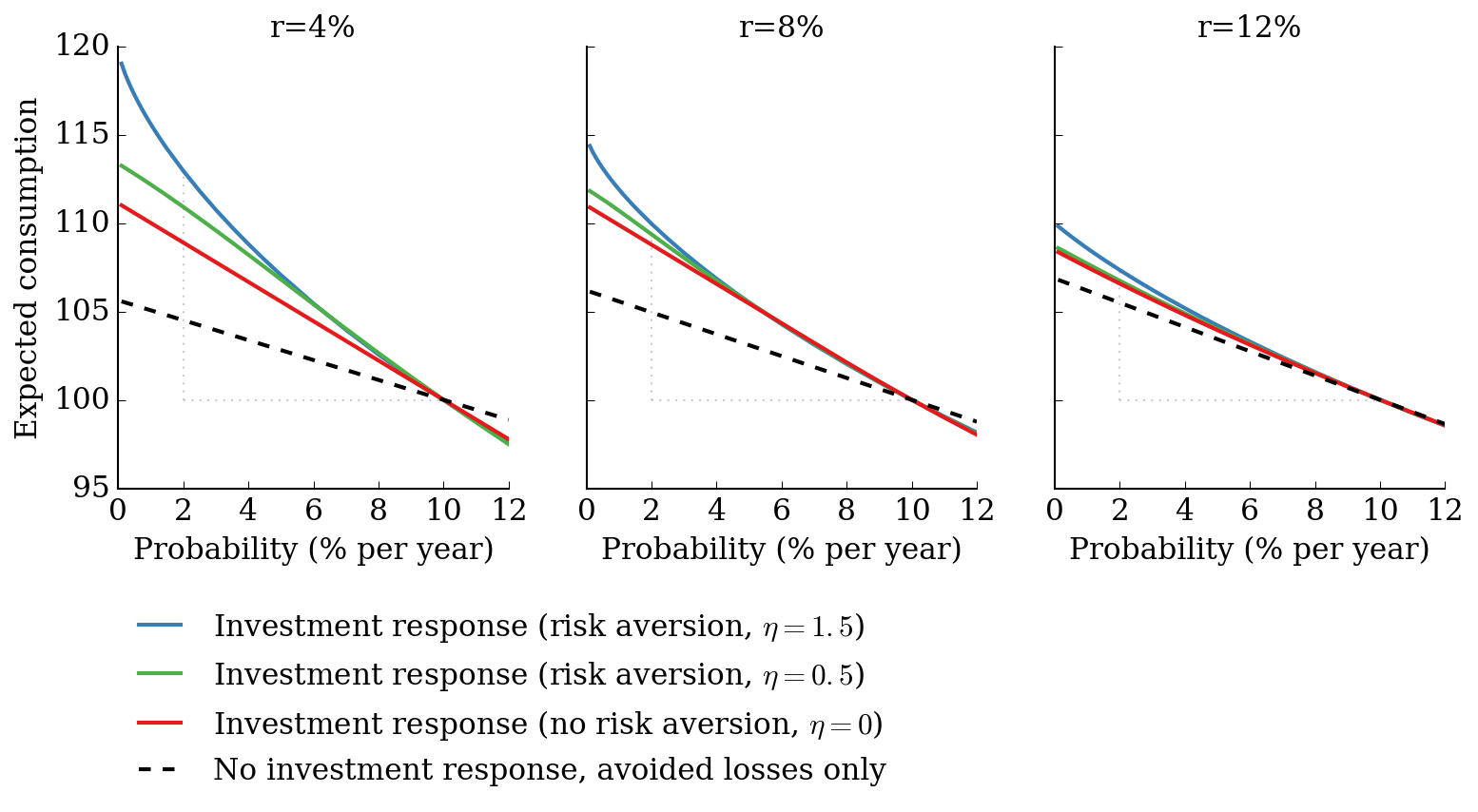


Figure X: How expected consumption in the affected region changes when the annual probability of occurrence of a disaster is reduced or increased, calibrated at 100 for a 10% probability of occurrence. The dashed line takes into account only avoided losses; the other lines account for the response of investment, with no risk aversion or full insurance (red); and with risk aversion at increasing levels (green and blue). Each panel has a different level of capital productivity (r) from 4 to 12 percent.

This figure shows that estimating the benefits assuming that the level of investment is fixed, and considering the avoided capital losses as the only benefit from the intervention, leads to underestimating the gain in expected consumption, and thus welfare. With risk aversion, the underestimation becomes even larger. The panels show that the effect is larger when risk aversion is larger, and when the interest rate (or marginal productivity of capital) is lower. For low risk aversion levels, the effect of risk aversion is only visible for very low probability of occurrence.

In developing countries, that fact that the productivity of capital is high (due to capital scarcity) decrease the importance of this mechanism; but low access to insurance and low consumption level are likely to lead to higher levels of risk aversion, magnifying this mechanism.

Let’s look at a flood protection package that would reduce flood probability from 10 to 2 percent, with a risk aversion and average productivity of capital (r=8%). Considering only avoided losses, with a fixed amount of capital in the risky area, reducing the probability of occurrence of a disaster from 10 to 2% increases expected consumption by 4.9%. If investment responds to the modified level of risk, but with no risk aversion or full insurance, then the amount of capital increase (by 9%), and the total benefit increases to 8.8%. Adding risk aversion into the picture, the reduction in risk leads to a larger increase in investment – and capital increases by 40%, leading to total benefit equal to 10% of pre-intervention consumption. Benefits are found to be 80% larger if the response of investment is taken into account, with no risk aversion or full insurance, and doubled if there is a significant aversion to risk.

This effect also plays a role for other types of intervention. If vulnerability is reduced by half, from 25 to 12.5%, the avoided capital losses are reduced so that expected consumption increases by 3% without changes in investment and capital. In the presence investment response, the benefits reach 5.5%, an increase by 80%, without risk aversion, and 8.7%, an increase by 180%, with risk aversion ().

Finally, the gap between avoided capital losses and total benefits becomes relatively larger as risk reduction increases. Consider an investment that reduces the probability of occurrence from 10% to almost 0%. Avoided capital losses would be equivalent to slightly more than 5% consumption increase, while the full benefits would be almost as much as 20% (figure X). In this case, the full benefits accounting for investment response are 300% times larger than direct benefits from avoided losses.

These results suggest that the impact of higher investment with lower risk level is large, even in the absence of risk aversion. And these results are robust since they only depend on a few well-known parameters, for which it is easy to run a sensitivity analysis: (1) the share of capital income (and the shape of the production function); (2) the interest rate; (3) the vulnerability of capital (i.e. the fraction of capital that is lost in case of disaster); (4) the initial probability of occurrence. Sensitivity analysis shows that as the initial probability of occurrence decreases, the effect of higher investment becomes smaller compared to avoided losses.

The impact of investment becomes even larger in the presence of significant risk aversion and in the absence of full insurance. It means that this effect is particularly large in low-income environment, where economic agents are close to the subsistence level and without risk management tools such as easy access to insurance or borrowing.

Increasing access to risk management tools such as insurance also has an economic benefit, even if it does not reduce the capital losses (and as long as moral hazard does not increase substantially capital losses). From the same equilibrium as before, with a 10% probability of occurrence and no insurance and a capital productivity at 8 percent, increasing the fraction of insured losses to 50% increases expected consumption by 3.2% with and 0.7% with .

With fixed investment and capital, introducing insurance does not affect the expected consumption: the benefits arise entirely from the smoothing of consumption; a more stable consumption with unchanged average value yields a high expected utility. In a framework where investment responds to the level of risk, there is an additional benefit from insurance, through increased investment in the area-at-risk, which is not negligible.

# Conclusion

The modeling of the macroeconomic impacts of natural disasters that is proposed here is extremely simple. It is not meant to replace more sophisticated represented of natural disasters impacts such as those based on Input-Output models (XX) or Calculable General Equilibrium Models (XX). It is meant to highlight the risk of underestimating the cost of natural disasters (and the value of rapid reconstruction) in simple models used for the cost-benefit analysis of disaster risk management investments or for climate change analyses.

First, it shows that using an aggregate production function may lead to underestimating the immediate impact of asset losses due to disasters on the economic output flow. It also proposes an alternative modeling to avoid this bias, by using the average – and not the marginal – productivity of capital to estimate the effect of asset losses on output. This results into an immediate reduction in output flow that is about three times larger than estimates based on the value of asset losses (and an aggregated production function). A better estimate of the impact on output is a critical input into the assessment of the benefits of risk reduction measures.

Second, this paper highlights the critical role of the reconstruction capacity and speed in the consumption (and welfare) impact of disasters. Again, the bias created when using only aggregated production function leads to underestimating the output impact of natural disaster, and to disregard the importance of reconstruction capacity as a critical determinant of welfare losses. This paper provides a simple way to estimate total consumption losses due to a disaster. It suggests that the (discounted) consumption losses due to a disaster are 10 percent larger than asset losses if reconstruction takes place in one year, and up to 80 percent is reconstruction takes place in 10 years. This provides the required inputs to estimate the economic benefits from improved reconstruction capacity (e.g., thanks to insurance or rainy-day funds).

Third, this paper highlights the importance of the “second dividend” of disaster risk reduction, namely the increase in investment and capital accumulation that would result from a reduction in the risk level. A simple and robust analysis suggests that the increase in the benefit from reducing the probability of occurrence of a disaster could be multiplied by between 20 and 190 percent, depending on the productivity of capital and population risk aversion.

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# Appendix A: price impacts and the cost of reconstruction

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. 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.[[11]](#footnote-12)

For large shocks, estimating the value of lost output 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.

Post-disaster price is especially sensible in the construction sector, which sees final demand soar after a disaster. For instance, Figure 2.4 shows the large increase in wages for roofers and carpenters in two areas heavily affected by hurricane losses in Florida in 2004. This inflation affects the replacement cost of capital and is referred to as “demand surge” in the insurance industry.





*Figure 2.4: Wages for qualified workers involved in the reconstruction process (roofer and carpenter), in two areas 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.*

Post-disaster price inflation is often considered as resulting from unethical behavior from businesses, justifying anti-gouging legislation (e.g., Rapp, 2006). But it also have positive consequences by supporting the optimal allocation of the remaining capital (e.g., housing) and by incentivizing quick reconstruction. This inflation, indeed, helps attract qualified workers where they are most needed and creates an incentive for all workers to work longer hours, therefore compensating for damaged assets and accelerating reconstruction. It is likely, for instance, that higher prices after hurricane landfalls are useful to make roofers from neighbouring unaffected regions move to the landfall region, therefore increasing the local production capacity and reducing the reconstruction duration. Demand surge, as a consequence, may also reduce the total economic cost of a disaster, even though it increases its financial burden on the affected population.

In extreme cases, or where price adjustment are constrained by ethical consideration or anti-gouging regulations, there may be rationing, i.e. the price cannot clear the market and supply is not equal to demand: 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.

1. In many estimates of households disaster losses, one can find “asset losses” and “income losses” (see for instance Patankar and Patwardhan, 2014). But in that case, it is often the case that “asset losses” represent the losses to the assets owned by the considered household and “income losses” represent the loss in income due to damages to other people’s (or public) assets. For instance, a household can lose its house (an asset loss) and be unable to work because its firm is damages (a loss to the firm’s owner asset) or because transportation is impossible (a loss of public assets). [↑](#footnote-ref-1)
2. Note that if the value of asset losses DK is defined as the discounted value of the lost production, then by definition the asset losses are equal to lost production. Here, we highlight the difference between the asset losses measured by their replacement cost and the lost production. [↑](#footnote-ref-2)
3. Also taking into account the curvature of the production function. [↑](#footnote-ref-3)
4. 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. [↑](#footnote-ref-4)
5. In growth model, the impossibility to relocate capital can be represented by a non-negativity constraint on investments: investments in capital K1 cannot be negative, with the divestment used to consume or invest in K2; see an example in Rozenberg et al. (2014). [↑](#footnote-ref-5)
6. Other assets may exhibit negative externality, e.g. air pollution from coal power plant. [↑](#footnote-ref-6)
7. 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>. [↑](#footnote-ref-8)
8. 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. [↑](#footnote-ref-9)
9. 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. [↑](#footnote-ref-10)
10. With full insurance, consumption C is independent of the state of the world, and investment is the same with and without risk aversion. [↑](#footnote-ref-11)
11. 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). [↑](#footnote-ref-12)