Chapter 2
What Is a Disaster? An Economic Point of View

Abstract This chapter focuses on the economic consequences of a disaster and discusses the definition of the "economic cost" of a disaster. It stresses that a natural disaster is not a natural event, but the combination of a natural hazard (e.g., a hurricane) with a human system that is exposed to it and suffers from damages and perturbations. It reviews concepts such as direct and indirect losses, market and non-market losses, and consumption and output losses. The chapter also describes some of the most important mechanisms that determine the economic consequences of a disaster, such as the response of prices or the propagation of impacts through supply chains. It reviews the various tools that have been developed to measure and assess output losses from disasters, covering econometric analyses, input-output and computable general equilibrium models. It concludes with a definition of economic resilience and stresses the fact that reducing disaster welfare impacts can be done by reducing direct losses or by building resilience.

Keywords Natural disaster • Economic cost • Economic models • Disaster risk management

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 and lightning.

If a hazard affects a human system – from one house to one region – and causes sufficiently larger negative consequences to this system, the event can then be labeled 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).

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. There are multiple formal definitions. The Center

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for Research on the Epidemiology of Disasters (CRED) at the Catholic University of Louvain – that maintains the EM-DAT database, see Box 2.1 – 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.

Defining the economic cost of a disaster also poses different theoretical and practical challenges. This chapter discusses these problems, and summarizes the most important mechanisms that determine the cost of disaster. It does so by first explaining why the direct economic cost, i.e. the value of what has been damaged or destroyed by the disaster, is not a sufficient indicator of disaster seriousness and why estimating indirect losses is crucial. Then, it describes the main indirect consequences of a disaster and of the following reconstruction phase, and discusses the methodologies to measure them.

2.1 Defining the Economic Cost of Extreme Events

After each large-scale disaster, media, insurance companies and international institutions publish numerous assessments of the "cost of the disaster." These various assessments are based on different methodologies and approaches, and they often reach quite different results. In the US, for instance, a systematic analysis by Downton and Pielke (2005) showed that loss estimates differ by a factor of 2 or more for half of the floods that cause less than $50 million in damages. These discrepancies are in part due to technical and practical problems, but also to the multi-dimensionality in disaster impacts and their large redistributive effects. Depending on what is included or not in disaster cost assessments, indeed, results can vary greatly. But the purpose of these assessments is rarely specified, even though different purposes correspond to different perimeters of analysis and different definitions of what a cost is.

This confusion translates into the multiplicity of words to characterize the cost of a disaster in published assessments: direct losses, asset losses, indirect losses, output losses, intangible losses, market and non-market losses, welfare losses, or some combination of those. It also makes it almost impossible to compare or aggregate published estimates that are based on so many different assumptions and methods.

2.1.1 Direct and Indirect Costs

Many authors (e.g., Pelling et al. 2002; Lindell and Prater 2003; Cochrane 2004; Rose 2004) discuss typologies of disaster impacts. 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, injuries and fatalities from collapsed buildings.

Direct losses are often classified into direct market losses and direct non-market losses.

Market losses are losses related to goods and services that are traded on markets, and for which a price can easily be observed. For most disasters, direct market losses are losses of assets, i.e. damages to the built environment and manufactured goods. They include the houses and buildings that are damaged or destroyed, the content of these buildings and houses (furniture, equipment, paper and data, etc.), and infrastructure (roads, bridge, etc.). These losses can be estimated as the repairing or replacement cost of the destroyed or damaged assets. Since building and manufactured goods can be bought on existing markets, their price is known: when a road is damaged, it is not difficult to estimate the cost of repairing it. Direct market losses can thus be estimated using observed prices and inventories of physical losses that can be observed or modeled (see Box 2.1 and an example in Table 2.1). Natural hazards also affect economic output, because offices and factories are closed during a storm for instance. For some hazards, such as heat waves and droughts, the main direct impact is on the economic output, not on assets: for instance a drought might not cause large damages to assets[1] but it can nevertheless reduce significantly agricultural production.

Non-market direct losses include all damages that cannot be repaired or replaced through purchases on a market. For them, there is no easily observed price that can be used to estimate losses. Non-market losses include health impacts and loss of lives, which are obviously a major component of natural disaster consequences. For instance, droughts can have permanent negative consequences on children development (e.g., diminished cognitive abilities) and floods are known to have large psychological impacts through post-disaster trauma. Disasters also damage historical and cultural assets, such as cathedrals and paintings, which have a high patrimonial value and are sometimes not exchanged on a market. Finally, disasters have impacts on natural assets and ecosystems, for instance when a hurricane leads to leaks of chemical products in the natural environment.

It is difficult to attribute a cost to non-market impacts, since they cannot be "repaired" or "compensated" through financial transfers. Sometime, a price for non-market impacts can be built using indirect methods, but these estimates are rarely consensual (more on this in Chap. 6).

One crucial aspect of disasters is that direct losses are not homogenously distributed. Investigating the 2004 hurricane season in Florida, McCarty and Smith

[1]Through its effect on soil dynamics, a drought may however cause large damages to buildings. The 2003 heat wave and drought over France is estimated to have cause damages to building larger than 1 billion euros.

(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. Of course, this heterogeneity depends on the hazard type: losses from hurricane winds are more homogeneous than flood losses, which can vary dramatically depending on the topography. **These results show that disaster damages are heterogeneous, with many small losses and few large losses, making average and aggregated loss estimates poor indicators of welfare impacts**.

Box 2.1: Available Data on the Economic Cost of Disasters

The emergency Events Database (EM-DAT) maintained by the Center for Research on the Epidemiology of Disasters (CRED) at the Catholic University of Louvain, Belgium (http://www.emdat.be) is an important source of publicly available data on natural disasters. This database is compiled from diverse sources such as international financial agencies (e.g., the World Bank), UN agencies, NGOs, insurance companies, research institutions and press agencies.

The amount of damage reported in the database consists only of direct damages (e.g., damage to infrastructure, crops, and assets). The data report the number of people killed, the number of people affected, and the dollar amount of direct damages for each disaster.

Reinsurance companies also provide an extensive source of data but with important limits:

- The data are not publicly available, or only in an aggregated fashion;
- Reinsurance companies are collecting data based on the losses insured, and are thus biased toward countries where insurance is well developed (i.e. rich countries).
- These data usually disregard all indirect and nonmonetary losses.

Some loss data are also produced by “catastrophe models,” developed to help insurers and reinsurers estimate natural disaster risks and set reinsurance premium. Such models exist where private reinsurance markets are well developed. They can estimate the losses caused by an event (e.g., on hurricane or one earthquake), using inventories of insured assets and models that predict the amount of damages caused by physical hazards (e.g., the value of damages to a house when wind speed exceeds 100 km/h). These models are usually run after each large-scale disaster to produce a first estimate of direct losses.

In the 1990s, the Economic Commission for Latin America and the Caribbean developed a formal methodology to assess disaster impacts, including indirect impacts. The ECLAC methodology (UN ECLAC 2003) assesses these impacts by a collection of data and information of various types

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Box 2.1 (continued)
(physical, monetary, and expert judgment) in each sector (see an example in Table 2.1). Indirect costs are estimated through collection of information from economic agents, governments and experts, taking in consideration particular aspects such as transport disturbances cost, loss of opportunities, etc. Of course, data from different sources need to be aggregated carefully to avoid gaps and double counting.

Indirect losses (also labeled "higher-order losses" in Rose 2004) include all losses that are not provoked by the disaster itself, but by its consequences; they are spanning over a longer period of time than the event, and they affect a larger spatial scale or different economic sectors.[2] Like direct losses, indirect losses can be market or non-market losses. They include several categories of losses, such as:

- *Emergency costs*, i.e. the cost of intervention in the short term, which can range from a few hours for small events to months in case of large scale disasters like Katrina in New Orleans in 2005 or the Tohoku Pacific earthquake in March 2011. These costs include search and rescue costs, medical costs, when taking care of many injured victims at the same time is needed. They can also include security issues, even though evidence suggests that disasters trigger more collaboration and mutual assistance than unrest and looting (Solnit 2009). These costs can be significant: after the landfall of Katrina in New Orleans, emergency costs have been estimated at US$8 billion.
- *Business interruptions, supply-chain disruptions, and lost production due to capital damages* often represent a large share of indirect losses. The Iceland volcano eruption in 2010 interrupted air transport for a week, i.e. canceled air transport over the North Atlantic even in absence of any capital loss. A damaged factory after a hurricane cannot produce until it is rebuilt or repaired, leading to output losses. Output losses are also due to complex interactions between businesses, such as production bottlenecks when one element of a supply chain is affected and paralyze the entire production process.
- *Macro-economic feedbacks*, include the impact of reduced final demand because consumers and businesses suffer from a reduced income (e.g., due to loss of jobs), and the effect of lost tax revenue on public demand.
- *Demand surge*, i.e. the increase in repair costs after large disasters, because of the lack of workers and materials compared with the increase in demand due to reconstruction needs.

[2]Unsurprisingly, different hazards communities have different approaches for defining indirect costs. Contentious issues may emerge around the edge of these definitions across hazard communities.

Table 2.1 Losses in the housing sector after the 2010 floods in Pakistan (US$ million)

	Housing stock		Other				
Province	Completely destroyed	Partially destroyed	Equipment	Water and sanitation infrastructure	Debris removal costs	Temporary shelter costs	Total losses
AJK	3.2	4.6	1.2	0.2	0.1	0.3	**9.6**
Balochistan	65	2.7	18.5	1	1.9	7.8	**96.9**
FATA	1.1	1.4	0.7	0.1	0.1	0.2	**3.6**
Gilgit-Baltistan	3.9	0	0.8	0	0.1	0.3	**5.1**
KPK	96.6	67.2	37.8	5.6	4	14.3	**225.5**
Punjab	125.7	97.9	54.7	18.4	5.6	20.1	**322.4**
Sindh	499.8	111.3	196.2	28.1	19.9	70.1	**925.4**
Total	**795.3**	**285.1**	**309.9**	**53.4**	**31.7**	**113.1**	**1,588.5**

Source: Preliminary damages and needs assessment. Global facility for disaster reduction and recovery (www.gfdrr.org)

- *Long-term adverse consequences on economic growth* are also possible because of changes in risk perception (including over-reactions) that can drive investors and entrepreneurs out of the affected area.
- *Long term consequences of health effects, psychological trauma and social network disruption* represent an additional source of indirect losses, which are subject of a growing interest. Beyond the direct welfare loss, indeed, these effects can reduce individual productivity and slow down development, economic growth, and poverty reduction. The consequences of evacuation on well-being and social networks can be larger, especially for poor households. Some of them are particularly dependent on informal social networks (e.g., for childcare), and these networks can be destroyed if evacuation is not organized to maintain them (McCarthy et al. 2006).
- *The impact on poverty or inequalities* is also sometimes included in the indirect losses. The landfall of Katrina on New Orleans has renewed attention on the larger weather vulnerability of the poorest communities within a country, and on the inequality-widening effect of disasters (e.g. 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 1.5–3.6 % point. Often, the poorest have little to lose in a disaster and the impact on their welfare is therefore invisible in aggregated economic statistics. The case study on floods in Mumbai in Chap. 6 illustrates this problem. If the aim of the assessment is to look at welfare impacts, focusing only on economic aggregates can be misleading.
- *The impact on security, cohesion, stability* is also important. The Katrina landfall highlighted long term local security aspects of disaster (e.g., on food security, individual security, civil unrest), with for instance a 70 % increase in crime rate between the pre- and post-Katrina periods (see Van Landingham 2007). Sometimes, disaster consequences on social cohesion and political stability can be large. Even though disasters are never the unique cause of political unrest or even violent conflict, they have been important triggers in some cases (e.g., Bangladesh in 1970 and 1971 after hurricane Bohla).

Some of these impacts can be captured using classical economic indicators, such as GDP. There are however several issues when using GDP change as an indicator for indirect 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, the capacity of GDP to be a good proxy for welfare is also discussed, see Box 2.2.

Box 2.2: How to Measure Welfare? Moving Beyond GDP
The limits of GDP as an indicator of economic performance are well known, and have been summarized in several recent reports (e.g., Stiglitz et al. 2010; OECD 2009). In particular, the "Commission on the Measurement

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Box 2.2 (continued)
of Economic Performance and Social Progress" report recalls the main shortcomings of current GDP measures: (1) the difficulty in measuring quality improvement in goods and services, which may lead to under or overestimation of real income growth; (2) government-produced goods and services are measured through their input value only, which may lead to underestimation of output change if government productivity increases. But beyond these limits, the report makes the case for shifting from measuring economic production to measuring welfare. To do so, it recommends several changes, and four of them are particularly important to investigate natural disaster consequences:

- Focus on income and consumption instead of GDP: welfare depends more on income and consumption than on GDP. In particular, an increase in depreciation (e.g., because new capital goods like computers depreciate more rapidly than older ones) may translate into an increase in investment, and thus into an unchanged GDP and a reduced consumption. Everything else being unchanged, such a change is negative for welfare but is not recorded in GDP. The Net Domestic Product (NDP) is the GDP net of depreciation and therefore takes this effect into account. Economic growth measured by NDP can be significantly different from economic growth measured with GDP. Since natural disasters affect capital depreciation and "force" reconstruction investments, the difference between GDP and consumption is critical: often a disaster can increase GDP through reconstruction investments, but this increase should not be considered welfare-enhancing.
- A specific case of depreciation is the depletion of natural resources. This depletion has direct consequences on our ability to use natural resources in economic production (e.g., water, oil). It has also a value linked to ethical consideration (our willingness to protect species and biodiversity, independently of the services they provide). Depletion could be captured by excluding the value of the natural resources harvested from the production value of sectors like mining and timber. Their production would then consist only in a pure extraction or logging activity, with a corresponding decrease in GDP. Or, depletion could be counted as depreciation, keeping GDP unchanged but reducing NDP. Disasters cause damages to natural resources and ecosystems, and taking into account natural capital in disaster assessments is thus very important.
- It is useful to take into account the concept of "defensive" expenditures (originally defined in Nordhaus and Tobin 1972). The cost associated to commuting is included in GDP, even though commuting does not yield direct welfare benefits but is only a requirement for other economic

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Box 2.2 (continued)

activities. Many authors have proposed to treat these expenditures as intermediate consumption rather than final products, and to exclude them from GDP. But defining what is defensive is sometimes complicated. For instance, a new park can be considered as a defensive investment against the disamenities of urban life, or as a positive investment for recreational purposes. Because natural disasters force some defensive investments, for protection or reconstruction, the taking into account of defensive expenditures is crucial in the measure of their impact on welfare.

- Finally, many authors stress the importance of distribution in measuring economic growth and welfare, and suggest looking not only at averages but also at more sophisticated measures (from simple medians to quintiles). The same monetary loss would have very different consequences depending on whom it affects. Poor households will be particularly vulnerable to loss of assets, compared with wealthy households (Santos 2007; Alderman et al. 2006). This effect can be largely reinforced if impacts affect populations that are close to the subsistence level (Dercon 2004, 2005; Carter and Barrett 2006); in that case, even a monetary loss that is minuscule at the aggregate level can then have very large welfare impacts (see on Mumbai, Chap. 5). This aspect is important when investigating natural disasters: depending on the initial situation of the affected population and on how resulting costs are shared in a country or in a community, the total impact on welfare can be very different (see also a discussion of how to take this into account in a cost-benefit analysis in Chap. 6).

Many alternative indicators have been proposed – including the World Bank's Adjusted Net Savings that take into account natural resources and social capital – but there is no consensus on these indicators and GDP is still the most widely used for policy making and assessment.

An obvious illustration of why indirect 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.

2.1.2 Defining a Baseline

A first difficulty in disaster cost assessment lies in the definition of the baseline scenario. The cost of the disaster has indeed to be calculated by comparing the actual trajectory (with disaster impacts) with a counterfactual baseline

trajectory (i.e., a scenario of what would have occurred in the absence of disaster). This baseline is not easy to define, and several baselines are often possible. Moreover, in cases where recovery and reconstruction do not lead to a return to the baseline scenario, there are permanent (positive or negative) disaster effects that are difficult to compare with a non-disaster scenario.

For instance, a disaster can lead to a permanent extinction of vulnerable economic activities in a region, because these activities are already threatened and cannot recover, or because they can move to less risky locations. In that case, the disaster is not a temporary event, but a permanent negative shock for a region. Also, reconstruction can be used to develop new economic sectors, with larger productivity, and lead to a final situation that can be considered more desirable than the baseline scenario. This improvement can be seen as a benefit of the disaster. It is however difficult to attribute unambiguously this benefit to the disaster, because the same economic shift would have been possible in the absence of disaster, making it possible to get the benefits without suffering from the disaster-related human and welfare losses.

For instance, hurricanes in 1806 and 1807 participated in the shift that occurred at la Réunion – a French island in the Indian Ocean – from coffee to sugar cane production. Indeed, it takes about 5 years for a coffee plant to start producing usable fruits. When the hurricanes hit, the need to start producing again as soon as possible drove farmers to plant sugar cane, an annual crop that can be harvested in a year. Moreover, coffee production was then considered more vulnerable to wind damages than sugar cane. But sugar cane production also has a different economic vulnerability to other stresses such as changes in food markets, consumer tastes, and agricultural subsidies. Therefore, it is difficult to assess whether the shift from coffee to sugar cane should be considered as a cost of the hurricanes (if sugar cane eventually reveals less profitable than coffee) or as a benefit (if sugar cane is more profitable than coffee). The final outcome depends on many other factors that can hardly be predicted at the time of the disaster.

This baseline issue – very common in economics – is not easy to deal with, and different scholars have used different techniques. Coffman and Noy (2012) use two nearby islands to assess the impact of hurricane Iniki. Since the hurricane affected only one island, the other can be used as a "control", i.e. as a proxy for the economic condition of the affected island if it had been spared. In the absence of a similar control, duPont and Noy (2012) use a statistical method to build a counter-factual for the Kobe economy, i.e. a scenario for the Kobe economy if no earthquake had occurred in 1995.

2.1.3 Assessment Purpose and Scope

Defining the cost of a disaster cannot be done independently of the purpose of the assessment. Depending on the purpose of the assessment, some of the cost components have to be included or not in the analysis. Different economic agents, indeed, are interested in different types of cost. Insurers, for instance, are mainly interested in consequences that can be insured. Practically, this encompasses mainly the cost of damages to insurable assets (e.g., damaged houses and factories), and short-term business interruption caused by the disaster (e.g., the impossibility to produce until electricity is restored).

For affected households, insurable assets are also a major component, but other cost categories are as important. Primarily, loss of lives, health impacts and perturbation to their daily life are crucial. In addition, households are concerned about their assets but also about their income, which can be reduced by business interruption or by loss of jobs, and about their ability to consume, i.e. the availability of goods and services.

At the society scale, all these aspects are important, but local authorities, governments and international institutions are also interested in other points. First, to manage the recovery and reconstruction period and to scale the necessary amount of international aid, they need information on the aggregated impact on economic production, on unemployment and jobs, on the impact of inequality and poverty, on local-businesses market-shares, on commercial balance, on collected taxes, etc. Second, to assess whether investments in prevention measures are desirable, they need the broadest possible assessments of the total disaster cost to the population, i.e. an estimate of welfare losses.

Moreover, disaster impacts can have positive or negative ripple-effects at the many scales. A neighboring region can benefit from the disaster because it captures market shares lost by the region hit by the disaster. The global economy can suffer from price effects, as shown by the significant rise in world oil prices that followed the landfall of hurricane Katrina in the Gulf Coast in 2005. Depending on the purpose and of the decision-making spatial scale, the perimeter of the cost analysis will be different. For instance, a country may want to assess the losses in the affected region, disregarding all out-of-the-region impacts, to calibrate the financial support it wants to provide to the victims. But a country may also want to assess total losses on its entire territory, including gains and losses outside the affected region, for example to assess the impact on its public finances.

2.2 Output Losses and Their Drivers

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.

2.2.1 From Asset Losses to Output Losses

Economic theory states that, at the economic equilibrium and under certain conditions, the value of an asset is the net present value[3] **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 interest rate (which is equal to the marginal productivity of capital). 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 2.1 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. This equality between output losses and capital losses is however based on strong assumptions, which are not always verified.

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.

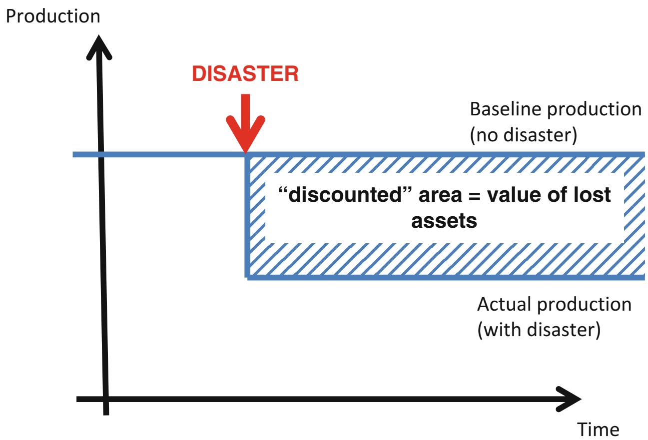

Fig. 2.1 Production as a function of time, without disaster or in a scenario with disaster and no reconstruction. In the latter case, the discounted value of the lost production (from the disaster to the infinity) is equal to the value of lost assets. The production decrease is equal to the value of lost assets multiplied by the interest rate

[3]Note that the net present value is the sum of the production, discounted to account for the fact that production far in the future has less value than more immediate production; see a discussion on the discount rate in Chap. 6 and especially Box 6.2.

In a theoretical and optimal economy at equilibrium – these two equalities are valid. First, if the market value of an asset is lower (resp. larger) than the net value of its output, then investors will buy more (resp. sell) more of this asset to capture the difference in value, making asset price increase (resp. decrease).

Second, if market value were higher (resp. 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 a realistic setting, however, these two assumptions are not always verified. The reasons why asset values and output losses can differ are discussed in the following.

2.2.1.1 The Economy Is Not at Its Optimum

For the replacement value and the market value to be equal, the economy needs to be at its 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 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 the 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 the society is larger than the value of the owner's expected output. Public goods have this characteristic, among which most infrastructures, health services, education services.

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 1 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 unlikely to exhibit decreasing returns and 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 (what economists call a "positive externality"). After Katrina's landfall on the city, the absence of health care services made it more difficult to reconstruct, and the cost for the region was much larger than the economic direct value of this service.

2.2.1.2 The Shock Is Large ("Non-marginal" in Economic Terms)

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 1,000 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 – leads to an output loss equal to the replacement cost of the car. But the destruction of many cars will affect cars with various productivity levels, and leads to an output loss that is larger than the replacement value of these cars.

Moreover, the equality of asset value and output depends on the assumption that the destructions affect the least productive assets only. In the previous example, 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 used car to its owner (which makes sense because the former makes a more efficient use of the car than the latter). Box 2.3 explains why this is unrealistic and why it leads to an underestimation of the output losses due to natural disasters.

As already stated, economic theory suggests that for marginal shocks, the annual loss in output should be equal to the value of lost assets multiplied by the interest rate (i.e. by the marginal productivity of capital). **In practice, it is more realistic to assess the loss of output as the value of lost assets multiplied by the average productivity of capital. Using classical production function and parameters (see Box 2.3), this approximation leads to output losses equal to approximately three times the value of lost assets**.

Box 2.3: The Use of Classical Production Function Leads to Underestimating Output Losses

There are several possible biases resulting from disaster modeling using classical production function (Hallegatte et al. 2007). Production functions are classically used in economics to relate the inputs and the outputs of a 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):

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Box 2.3 (continued)

$$Y = f(L, K).$$

Disasters mainly destroy the stock of productive capital and a natural modeling option to represent their consequences is to consider that they reduce instantaneously the total productive capital ($K_0 \rightarrow K_0 - \Delta K$). Figure 2.2 illustrates several ways of assessing the impact on production. 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.

The impact on production can be estimated using the marginal productivity of capital, i.e. the interest rate at the optimum. This case is shown in Fig. 2.2 as the point B. Point B is estimated using the orange 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 do I get if I increase capital by one unit). The production 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 interest rate. It is also what is done when the net present value of all output losses is assumed to be equal to the value of lost assets.

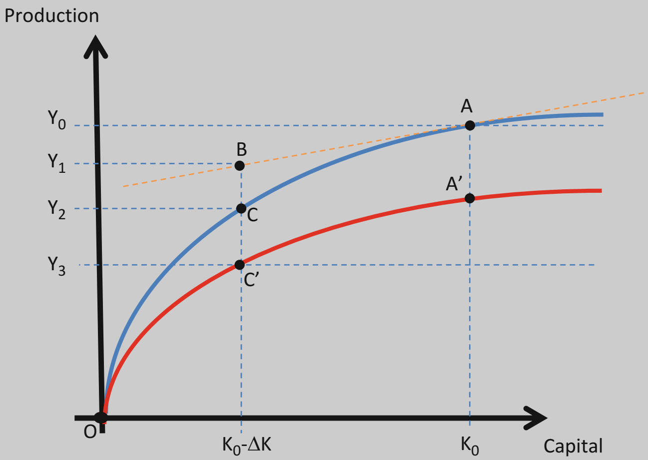

Fig. 2.2 Production with respect to productive capital for different modeling assumptions

(continued)

Box 2.3 (continued)

The impact on production can also be estimated using 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 the figure. The point C gives the value of production Y_2 given by the production function, i.e., $f(L,K_0 - \Delta K)$. This option, however, amounts to assuming that only the least-productive capital has been affected. Obviously, this is not the case: when a disaster hits, it destroys the capital indiscriminately, not only the least efficient capital.

Because of decreasing returns in the production function, using a classical production function amounts to assuming that capital destructions affect only the less efficient capital. In a Cobb–Douglas setting ($Y = AL^{\lambda}K^{\mu}$), indeed, the after-disaster production would be $Y_2 = AL^{\lambda}(K_0 - \Delta K)^{\mu}$. Since μ is classically estimated around 0.3, anx% loss of equipment would reduce the production by a factor (μ x), i.e. approximately (0.3 x) % (see figure below).

To account for the fact that disasters affect the capital independently of its productivity, 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. The new production function is

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

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 3.3 times ($=1/\mu$) the loss of asset estimated using the normal production function. In Fig. 2.2, the new production function is the red line and the new production Y_3 is given by the point C′.

Another bias arises from the aggregation of many different types of capital within only one variable – capital K – in economic models. If the function f(L,K) is replaced by a function with two types of capital $f(L,K_1,K_2)$, the impact of disasters can change dramatically. In particular, because of 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 one type of capital, compared with a scenario where the two capitals are more homogeneously affected. As a result, disaster loss estimates can be dependent on the aggregation level of the economic models used to assess them: the more disaggregated the model is, the more likely it is that one type of capital is heavily affected, leading to large output losses (see also Sect. 2.4.2).

The use of production functions may create another problem: production functions assume that the output of the production process is continuous in

(continued)

Box 2.3 (continued)
K and L. In reality, there are discontinuities in the production function: the loss of a segment of a road can make the entire road impracticable and useless; damages to one small piece of equipment in a factory can make it unable to produce the final product, etc. So a small ΔK can lead to a large loss in output, if the complementary of different capital items is taken into account. This is especially true when large network infrastructure is concerned.

Asset and output losses are often estimated assuming unchanged (pre-disaster) prices, which is valid only for marginal shocks. One can assume that if a house is destroyed, the family who owns the house will have to rent another house at the pre-disaster price. In other terms, the value of the housing service provided by the house can be estimated by the rental cost of a similar house before the disaster. 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. For large shocks, estimating the value of lost housing service should take into account the price change (even though, as shown in Box 2.4, it is challenging to do so). 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, health, etc.

In extreme cases, there may be rationing, i.e. the price cannot clear the market and supply is not equal to demand (Bénassy 1993). This is because markets are not at equilibrium in disaster aftermath. The « If I can pay it, I can get it » assumption is not 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, therefore, the welfare impact of lost production cannot be estimated as the product of lost produced quantity and pre-disaster prices. Providing an unbiased estimate requires an assessment of the disaster impact on prices and taking into account rationing.

Box 2.4: Quantity and Prices in Disaster Aftermaths
Figure 2.3 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 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

(continued)

Box 2.4 (continued)

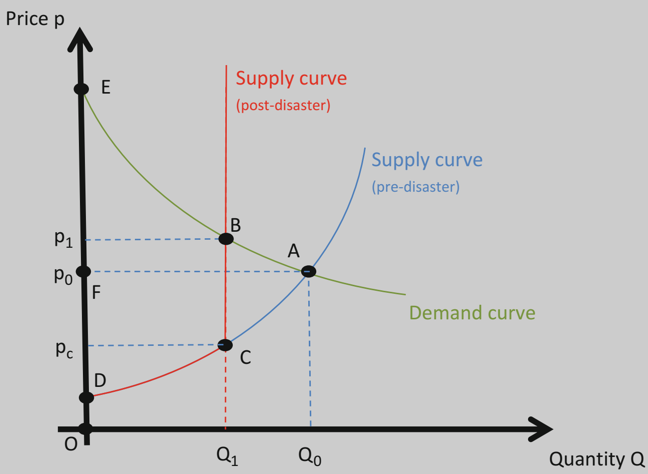

Fig. 2.3 Supply and demand curves in the pre- and post-disaster situations

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.

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,

(continued)

Box 2.4 (continued)
a reduction in intermediate is not a gain (and intermediate consumptions are not included in the GDP). 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: $(p_0 + p_1)\ \Delta Q/2$.

Post-disaster price inflation (also referred to as "demand surge") is especially sensible in the construction sector, which sees final demand soar after a disaster. For instance, Fig. 2.4 shows the large increase in wages for roofers and carpenters in two areas heavily affected by hurricane losses in Florida in 2004. Demand surge is often considered as resulting from unethical behavior from businesses, justifying anti-gouging legislation (e.g., Rapp 2006). But demand surge can also have positive consequences. 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 neighboring 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.

2.2.2 "Ripple Effects"

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 secondary effects, sometimes referred to as "ripple effects".

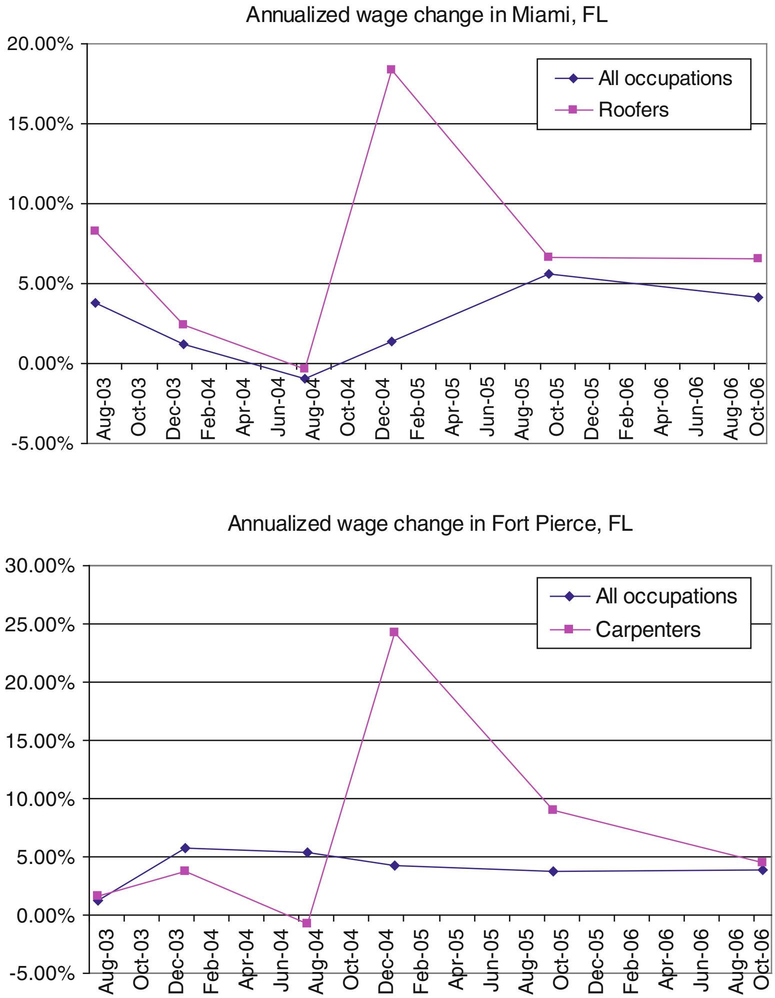

Fig. 2.4 Wages for qualified workers involved in the reconstruction process (roofer and carpenter), in two areas where losses have been significant after the 2004 hurricane season in Florida (Data from the Bureau of Labor Statistics, Occupational Employment Surveys in May 03, Nov 03, May 04, Nov 04, May 05, May 06, May 07)

This is particularly the case for infrastructure and utility services (electricity, water and sanitation, gas, etc.). In past cases, it has been shown that the loss of utility services had larger consequences than direct asset losses, both on households (McCarty and Smith 2005) and on businesses (e.g., Tierney 1997; Gordon et al. 1998).

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**

Table 2.2 Reason for businesses to close following the Northridge earthquake

Reason	Percentage	Local (L) or indirect (I)
Needed to clean-up damage	65.2	L
Loss of electricity	58.7	I
Employees unable to get to work	56.4	I
Loss of telephones	49.8	I
Damage to owner or manager's home	44.4	I
Few or no customers	39.9	I
Building needed structural assessment	31.5	L
Could not deliver products or services	24.0	I
Loss of machinery or office equipment	23.7	L
Building needed repair	23.4	L
Loss of inventory or stock	21.9	L
Loss of water	18.2	I
Could not get supplies or materials	14.9	I
Building declared unsafe	10.1	L
Could not afford to pay employees	9.5	L
Loss of natural gas	8.7	I
Loss of sewer or waster water	5.3	I
Other	15.8	?

Source: Tierney (1997)
The reasons linked to local damages to the business are highlighted in *yellow*; the others are indirect reasons, due to perturbations in infrastructure services such as transport or electricity

because of the loss of utilities (e.g., they had no running water). In only 37 % of the cases, the main reason was structural damages to the house. Of course, households forced to move by direct losses to their home could not return as rapidly as the others, and they represent the majority of those who had to move out for more than a month (about 15 % of the households who had to move).

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, see Table 2.2. The first reason, with 65 % of the answers (several answers were possible), is the need for clean-up. After that, the five most important reasons are loss of electricity, employee 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 %. All 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 at 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 have been restored rapidly; only transportation issues have led to long lasting consequences.

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.[4] These ripple-effects can be labeled "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 (see Box 2.5).

Some inputs are absolutely necessary for production, and a short interruption can cause significant perturbation in production. Examples are electricity, water, fresh goods, and all other goods that are required for production and cannot be stocked. Other inputs are also necessary for production, but they can be stocked, and a short interruption in supply does not create large difficulties. An example is steel and tires for automakers, which are indispensable but stockable. Finally, other inputs are not absolutely necessary for production, and reasonably long interruptions can be managed. This is the case for instance of many business services, education and professional training.

Inventories matter because they mitigate bottlenecks in the production system, introducing an additional – and critical – flexibility into the system. Modern production organization tends to reduce the use of inventories with production-on-demand and just-in-time delivery. Added to other trends (e.g. outsourcing, reduction in the number of suppliers), these changes may make each production unit more dependent on the ability of its suppliers to produce in due time the required amount of intermediate goods. As a result, these changes may increase the overall vulnerability of the economic system to natural disasters, in a trade-off between robustness on the one hand, and efficiency in normal times on the other hand.

One can show that the output losses due to a disaster depend on the characteristics of the firm-to-firm networks (Henriet et al. 2012), such as the average number of suppliers that firms have, or the shape and structure of the connection between firms:

- *High-concentration* economies (i.e. economies where firms rely on a few suppliers only) are more vulnerable to disasters. This effect is magnified if firms have small inventories.
- *High-clustering* economies (i.e. an economy in which suppliers of a firm are likely to also be its clients) are less vulnerable to disasters; examples of clustered economies are "localized" economy, in which clients and suppliers are close to each other, compared to a "specialized–globalized" economy in which there are global supply chains.

[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.

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. But the model used in Henriet et al. (2012) is too simple for providing realistic assessment of disaster costs, and detailed information on real-world economic networks is not available.

When capital cannot produce because of a lack of input (e.g., electricity, water), several options are available: input substitution, production rescheduling, and longer work hours can compensate for a significant fraction of the losses (see Rose et al. 2007). These mechanisms can damp 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.

Box 2.5: The Tohoku-Pacific Earthquake in Japan and the Auto Industry
The impact of disasters on supply chains are tragically illustrated by the recent Tohoku-Pacific earthquake in Japan, and its wide consequences on industrial production and exports, especially in the auto industry. As an example, The Economic Times, an Indian newspaper, reports 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.*"

The New York Times also reports on the impact on Honda production: "*But auto production in Japan is at only half the normal level for Honda – as it is for Honda's bigger rivals, Toyota and Nissan. That is mainly because many of the 20,000 to 30,000 parts that go into a Japanese car come from the earthquake-stricken region in north-eastern Japan, where numerous suppliers were knocked off line. Unless part makers can resume production soon, the auto companies might have to shut down once again. 'We cannot continue for a long time,' said Ko Katayama, the general manager at Honda's factory here, declining to specify how long production could continue. Sooner or later, it's going to run out.*" These examples refer to highly-visible global supply chains, but such bottlenecks can also occur at the local scale, and even for small businesses.

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.

The "adaptability" and "flexibility" of the production system and its ability to compensate for unavailable inputs is largely unknown and largely depend on the considered timescale. Over the very short term, the production system is largely fixed, and the lack of one input can make it impossible to produce. Moreover, over short timescales, local production capacity is likely to be highly constrained by existing capacities, equipment and infrastructure. Only imports from outside the affected region and postponement of some non-urgent tasks (e.g., maintenance) can create a limited flexibility over the short-term. Over the longer term and the entire reconstruction period, which can stretch over years for large-scale events, the flexibility is much higher: relative prices change, incentivizing production in scarce sectors; equipment and qualified workers move into the affected region, accelerating reconstruction and replacing lost capacities; and different technologies and production strategies can be implemented to cope with long-lasting scarcities. The production system organization can also be adjusted to the new situation: one supplier that cannot produce or cannot deliver its production (because of transportation issues, for instance) can be replaced by another supplier; new clients can be found to replace bankrupt ones; slightly different processes can be introduced to reduce the need for scarce inputs (e.g., oil-running backup generator can be installed if electricity availability remains problematic).

Disaster indirect losses depend on the ability of the economic system to channel post-disaster residual production toward its best use, in order to minimize disaster losses. Using existing production for reconstruction (instead to "normal" demand) accelerates reconstruction and reduces total losses (see Box 2.3). It is also more efficient to use output to satisfy intermediate demands from other sectors, to allow these other sectors to function and create value. The ability of the economic system to do so depends on how its institutions and markets can identify the "most important" demands (i.e. the demands that increase welfare most) and direct production toward these demands.

First, the possibility to channel output toward the most productive use depends on the homogeneity of goods and services within each sector. For instance, is it possible to divert some production that was directed toward final consumers to another industry intermediate demand? Doing so is possible if the produced goods are identical (e.g., the same car can be used by a final consumer or by another business); but in most cases, intermediate demands and final demands concern different goods and services (e.g., in cities, it is possible to have scarcity of residential housing but unused office space).

Second, determining the optimal distribution of goods and services is indeed extremely difficult since it requires the taking into account of all supply-chains and business relationship in the economic system, i.e. a perfect knowledge of the economic network. Theoretically, prices can play this role as they include all existing and necessary information. If prices were perfect, they would make it possible to optimize the use of remaining production capacities. For instance, if prioritizing intermediate consumptions over final demand increases total output and population well-being, then firms should be able to out-bid final consumers (i.e. they would be ready to pay a higher price) and they would capture the production they need. Over the short-term, however, prices are unlikely to include all information: they take a long time to adjust to new conditions, and different economic, governance and political processes have an influence on them. In particular, a producer that is unable to satisfy all the demand – and has to ration some of its (frustrated) clients – is very unlikely to also impose price hikes to them. Moreover, natural disasters are situations of abnormal solidarity and assistance (Solnit 2009) and price increases that reflect real scarcity will appear socially and politically unacceptable in disaster aftermaths.

2.2.3 Non-linearity in Output Losses and Poverty Traps

There are two main reasons why output losses are likely to increase non-linearly with the size of the disaster (and the amount of destruction). First, 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).

Second, the reconstruction capacity is always limited by financial and technical constraint and it makes rebuilding after a large scale disaster much longer than after a small one. In other terms, the duration of the shock increases with its amplitude. 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.

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 correspond to 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 by Box 2.3). One source of friction is that consumers, insurance and re-insurance companies, other companies and public organizations need time to direct high amounts of money to reconstruction activities. This constraint is crucial in developing economies (Benson and Clay 2004). Another source of friction is that the sectors involved in reconstruction activities have skills and organizational capacities adapted to the normal state of affairs and cannot face huge increases in demand (after the French storms in 1999 or after the AZF explosion in Toulouse in 2001, reconstruction took several years because roofers and glaziers were not numerous enough).

A model-based investigation of this issue using the Adaptive Regional Input-Output (ARIO) model (see a discussion on modeling in Sect. 2.4.2 and Hallegatte 2008, 2014) concludes that total losses due to a disaster affecting Louisiana increase nonlinearly with respect to direct losses when direct losses exceed $50 billion (see Fig. 2.5). When direct losses are lower than $50bn, aggregated indirect losses are close to zero (even though the aggregation hides important disparities among

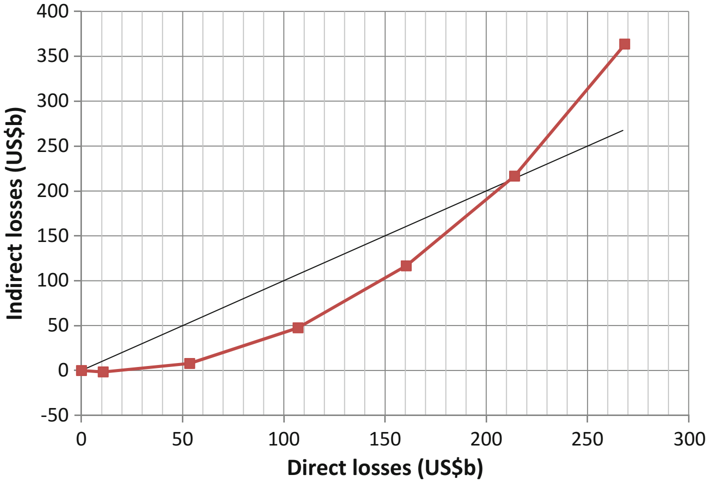

Fig. 2.5 The direct losses – indirect (output) losses as a function of direct (asset) losses, in Louisiana for Katrina-like disasters of increasing magnitude

sectors and among social categories). Beyond \$50 billion of direct losses, indirect losses increase nonlinearly. When direct losses exceed \$200 billion, for instance, total losses are twice as large as direct losses. For risk management, therefore, direct losses are insufficient measures of disaster consequences.

The output losses due to a hazard (and the resulting welfare impact) do not depend only on the physical intensity of the natural event, but also on the coping capacity of the affected human system. Physical measures of disaster intensity (e.g., in m/s for windstorm) or even measures of direct losses (e.g., the number and value of destroyed and damaged buildings) are very poor proxies of the real economic cost of a disaster.

A corollary is that natural disasters can have significant macroeconomic impacts, when they are larger than the (context specific) economic coping capacity. Moreover, it means that reducing natural disaster impacts on welfare can be done through an increase of the coping capacity, to make reconstruction faster and more efficient and limit output losses.

This non-linearity could even lead to macro-level poverty traps, in which entire regions could be stuck. Such poverty traps could be explained by the amplifying feedback reproduced in Fig. 2.6: poor regions have a limited capacity to rebuild after disasters; if they are regularly affected by disasters, they do not have enough time to rebuild between two events, and they end up into a state of permanent reconstruction, with all resources devoted to repairs instead of addition of new infrastructure and equipment; this obstacle to capital accumulation and infrastructure development lead to a permanent disaster-related under-development.

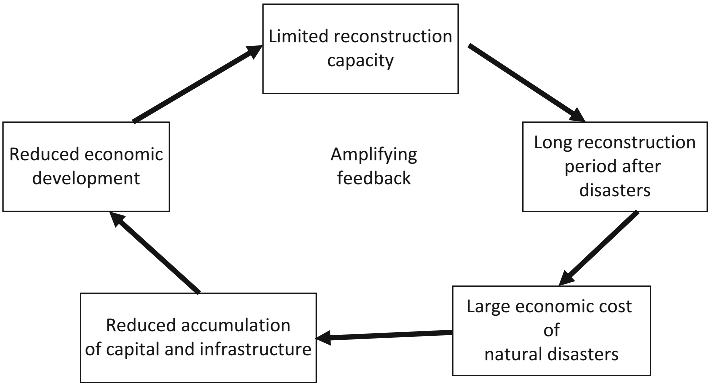

Fig. 2.6 Amplifying feedback loop that illustrates how natural disasters could become responsible for macro-level poverty traps

This effect has been analyzed in Hallegatte et al. (2007)[5] that suggests that the long-term average GDP impact of natural hazards in one given region can be either close to zero if reconstruction capacity is large enough, or very large if reconstruction capacity is too limited (which may be the case in some least developed countries).

In the model, there is a brutal "bifurcation" between two possible situations:

- **Either disasters are small enough with respect to the reconstruction capacity, and disasters are short-term events with potentially large immediate impacts but a limited influence on long-term income and growth;**
- **Or disasters are too large (i.e. too frequent or too intense) with respect to the reconstruction capacity, and in that case disasters can have a significant impact on income and growth and development prospects**.

This type of feedback can be amplified by other long term mechanisms, like changes in risk perception that reduces investments in the affected regions or reduced services that make qualified workers leave the regions. Hallstrom and Smith (2005) assess the impact of hurricane risk perception on housing values in Florida, and find that hurricane risks reduces property values by 19 %. Such an impact on housing price can have broad consequence on economic activity, over the long term.

[5]This analysis was performed using the NEDyM model. This model is a highly idealized macroeconomic model that follows the classical Solow growth model in considering an economy with one representative producer, one representative consumer and one good, used both for consumption and investment. The original Solow (1956) model is composed of a static core describing the market equilibrium, and a dynamic relationship describing the productive capital evolution. In NEDyM, the static core is replaced by dynamic laws of evolution, building delays into the pathways toward equilibrium.

2.2.4 Building Back Better? The Productivity Effect

When a disaster occurs, it has been suggested that destructions can foster a more rapid turn-over of capital, which could yield positive outcomes through the more rapid embodiment of new technologies. This effect, hereafter referred to as the "productivity effect" (also labeled "Schumpeterian creative destruction effect"), has been mentioned for instance by Albala-Bertrand (1993), Okuyama (2003), and Benson and Clay (2004).

Indeed, 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.[6] Examples of such upgrading of capital are:

(a) For households, the reconstruction of houses with better insulation technologies and better heating systems, allowing for energy conservation and savings, and with a better resistance to natural disasters;
(b) For companies, the replacement of old production technologies by new ones, like the replacement of paper-based management files by computer-based systems, or new machines that are more effective and consume less energy;
(c) For government and public agencies, the adaptation of public infrastructure to new needs, like the reconstruction of larger or smaller schools when demographic evolutions justify it.

Capital losses can, therefore, be compensated for by a higher productivity of the economy in the event aftermath, with associated welfare benefits that could compensate for the disaster 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.

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. Replacing the destroyed capital by the most recent type of capital implies in most cases to adapt company organization and worker training, which takes time. Producers have thus a strong incentive to replace the destroyed capital by the same capital, in order to restore production as quickly as possible, even at the price of a lower productivity. In extreme cases, one may even imagine that reconstruction is carried out with lower productivity, to make reconstruction as fast as possible, with a negative impact on total productivity (see how insurance can help in Box 2.6).

[6] On a related issue, it has been shown by Qing and Popp (2013) that natural disasters could trigger innovation in risk-mitigation technologies.

Box 2.6: The Role of Insurance and Reinsurance

The insurance industry plays a specific role in dealing with natural disasters. For small-scale events and uncorrelated risks, insurance is based on spreading risks among insurance customers. Because there is more or less the same number of car-insurance customers who have a car accident every year – the risk is said to be non-correlated –, it is possible to share this risk among them. Every year, the insurance premiums paid by all customers pay for the claims of those who have an accident. For individuals, the possibility of a large loss due to an accident is replaced by a certain and small payment every year. If agents are risk averse, this increases their welfare.

For correlated risks like large scale disasters, on the other hand, this principle no longer works: in any given year, there is either no disaster and there is no claim to pay, or one or more disasters and there are many claims to pay. In that case, the risk cannot be spread among customers of a single insurer portfolio in a single year, and need to be spread over time and over space. This is the role of reinsurance companies, which are global companies and keep a large amount of capital to pay a large number of claims in the same year in case of large-scale disaster(s).

The reinsurance companies are the insurers of the insurance companies. Their main activities include the coverage of frequency risk, catastrophe risk and longevity risks (in the case of life-insurance). Contracts, named treaties, are passed between a reinsurance company and the ceding insurer, determining the portfolio covered, the risk considered and the level of coverage. In the case of catastrophe insurance, the role of reinsurance is triple (1) it provides insurance companies with additional capacity to cope with correlated risks; (2) it allows for a worldwide mutualization of losses; (3) it provides an expertise on the risk insurers undertake. This third aspect of counseling particularly concerns insurance companies of medium and small sizes that do not have access to sufficient knowledge on the catastrophe risks.

Insurance is useful for several reasons:

- First, it spreads the risk among customers, over space, and over time. By doing so, it replaces rare and large losses by regular and small payments. If economic agents are risk averse, they prefer smooth and regular losses to an unknown and potentially large loss, and insurance increases welfare.
- If a disaster occurs, insurance claims support the affected population, reducing immediate welfare losses. Also, it helps fund the reconstruction and makes it shorter. As a consequence, output losses are reduced (see an illustration on Mumbai in Chap. 5).
- Because insurance provides a substitute income in disaster aftermath, it allows affected businesses and individuals to design and implement reconstruction strategies that take into account the most recent technologies.

(continued)

Box 2.6 (continued)

Such reconstruction strategies are longer to undertake than recreating an identical production system. Affected agents, therefore, would carry them out only if they have an alternative source of income during reconstruction.

- Most economic agents are not aware of the risk they are facing. If insurance premiums are risk-based (which is not the case in most of the world), they provide an accessible measure of the level of risk. This signaling effect can help households and businesses make smarter choices (e.g., settling in lower-risk areas), and be an incentive to risk-mitigation actions (e.g., by reducing insurance premium if homeowners invest in flood-mitigation). In a situation of climate change, in which risk levels will change over time, a risk-based insurance premium may help disseminate information on changing climate conditions and be part of an adaptation strategy. The signaling effect of risk-based insurance premium should not be overstated, however. In many places, it would be too small to trigger significant behavioral changes.

Finally, any analysis of insurance should take into account affordability and solidarity issues. If current insurance premiums were transformed overnight into risk-based insurance premiums in Florida, many homeowners would face affordability issues. This is why some have proposed to combine the introduction of risk-based premium with the distribution of "insurance vouchers" to poor households, in an effort to mitigate adverse distributional impacts for the most vulnerable (Michel-Kerjan and Kunreuther 2011).

Also, it is important to note that there are limits to the amount of risk private actors can accept, and the highest risk levels (e.g., a large-scale earthquake in Japan, a hurricane on New York) will always remain with the government and public authorities. This risk transfer to public authorities can be made explicitly (like in France with the Cat-Nat system or in the US with the National Flood Insurance Program (NFIP)) or implicitly (like where the federal government helped non-insurers homeowners in Louisiana after the landfall of Katrina in 2005).

Second, even when destructions are quite extensive, they are rarely 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 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 inheritance effect may for instance explain why it is almost never decided to reconstruct elsewhere – in the safer area – when a city located in a very risky location is affected.

In a simple economic model with embodied technical change (Hallegatte and Dumas 2008), disasters are found to influence the production level (i.e. average production is lower in areas with many disasters) but cannot influence the economic growth rate.[7] 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.

Moreover, productivity is not only a function of the technology and physical capital that is installed. Disasters can have long-lasting consequences on psychological health (Norris 2005), and on children development (from reducing in schooling and diminished cognitive abilities; see for instance Santos 2007; Alderman et al. 2006). Migrations can also play a big role. They constitute a response to extreme events and disasters, especially in developing countries (McLeman and Smit 2006; Landry et al. 2007; Dillon et al. 2011). But they have consequences on long term development, especially if high-skilled, high-productivity workers are more able to migrate than the average population (as suggested by the Katrina case; see Zissimopoulos and Karoly 2007). These mechanisms can lead to a long-term reduction in labor productivity, potentially compensating gains from more recent capital.

2.2.5 The Stimulus Effect of Disasters

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. However, as any stimulus, its consequences depend on the pre-existing economic situation, such as the phase of the business cycles. If the economy is 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.

This complex interplay between business cycles and natural disasters economics is analyzed in detail in Hallegatte and Ghil (2008). The paper analyses disaster vulnerability in different phases of the business cycle in a simple model. In this model, this business cycle originates from the instability of the profit–investment relationship, a relationship similar to the Keynesian “accelerator–multiplier.” When final demand is growing, firms need additional capacity to satisfy it, and they invest in new factories and other capacities. Doing that, they increase final demand

[7] This is similar to the fact that a change in the saving ratio in a Solow growth model can influence the output level, not the growth rate.

(because they buy buildings and factory and business equipment) and employment (because they hire workers). As a result, the initial increase in demand is amplified, leading to rapid growth. But part of this growth is unsustainable: it becomes more and more expensive to add capacity, with tensions on the labor market and decreasing returns of investments. At one point, profits become too low to justify additional capacity, and firms stop investing, leading to a drop in demand. At that point, the same mechanisms play, but in reverse: the decrease in demand due to lower investments means that there are excess capacities in the economy, and the economic stalls until wages have decreased and excess capacities have been resorbed (and profits are up again). The succession of these phases leads to the ups and downs of the business cycle.

When affected by natural disasters, the model supports the counter-intuitive result that economies in recession are more resilient to the effects of natural disasters. This result appears consistent with empirical evidence. For instance, the 1999 earthquake in Turkey caused direct destructions amounting to 1.5–3 % 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 have increased economic activities 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). The reconstruction needs had a stimulus effects on the construction sectors, which would have been impossible in a better economic situation.

There is a "vulnerability paradox":

- **A disaster that occurs when the economy is depressed results in lower damages**, thanks to the stimulus effect of the reconstruction, which activates unused resources. In this situation, since employment is low, additional hiring for reconstruction purposes will not drive the wages up to a significant extent. Moreover, the inventories of goods during the recession are also larger than at equilibrium; a disruption of production, therefore, can be damped by drawing on them. In this case, the economic response damps the lasting costs of the disaster, according to the model.
- **A disaster occurring during the high-growth period results in larger damages**, as it worsens pre-existing disequilibria. First, the inventories are below their equilibrium value during the high-growth phase, so they cannot compensate for the reduced production. Second, employment is at a very high level and hiring more employees induces excessive wage inflation, thereby constraining economic activity.

This apparently paradoxical effect, however, is consistent with Keynes' ideas: "*If the Treasury were to fill old bottles with banknotes, bury them at suitable depths in disused coalmines which are then filled up to the surface with town rubbish, and leave it to private enterprise on well-tried principles of laissez faire to dig the notes up again [. . .] there need be no more unemployment [. . .]. It would indeed be* *more sensible to build houses and the like; but if there are political and practical difficulties in the way of this, the above would be better than nothing*." In fact, it is not much different to increase demand through fiscal or budgetary policies than through the destruction of houses and production capital that need to be replaced as rapidly as possible. In the latter situation, agents increase their consumption and reduce their savings, thus leading to a rise in demand. It is also well-known that this approach to macroeconomic stabilization is useless if supply is constrained, which is the case during the expansion phase of the business cycle.

The stimulus benefits may be considered as a positive outcome of disasters, but the same effect would have been possible in the absence of a disaster, through a standard stimulus policy, and without the negative welfare and human impacts that come with disasters. So, it would be improper to attribute this positive effect to the disaster itself, and aggregating the corresponding benefits with disaster costs could be misleading on the real welfare cost of a disaster.

2.3 From Output Losses to Welfare Losses

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

Let's consider 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). 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 damages capital). In that case, consumption losses are thus simply equal to the value of lost assets.

Let's now consider another scenario with no reconstruction, in which output losses are permanent (like in Fig. 2.1) and all losses in output are absorbed by a reduction in consumption. In that case, consumption losses are equal to output losses. In the theoretical case in which output losses are equal to the value of lost assets, therefore, consumption losses are identical in these two scenarios.

There is a continuum of scenarios between these two extremes, with reconstruction that can be very rapid or very long. But as long as output losses are equal to the value of lost assets, the loss in consumption is unchanged and equal to the value of lost assets.

In the simplistic case where output losses are equal to the value of lost assets, the consumption losses are independent on the reconstruction scenario, and equal to the value of lost assets. Section 2.2 showed however that output losses are larger than the value of lost assets, and that the instantaneous loss of output is larger than what is suggested by the marginal productivity of capital. Because of these differences, the two extreme scenarios (instantaneous reconstruction and no reconstruction) are not equivalent.

In the instantaneous reconstruction scenario, consumption losses are equal to the share of consumption needed to repair and rebuild, i.e. the value of lost assets. In the no-reconstruction scenario, consumption losses are equal to output losses, i.e. larger than the value of lost assets.[8] **As a result, consumption (and welfare) losses are magnified when reconstruction is delayed. The reconstruction phase, and the economic recovery pace, will ultimately determine the final cost of the natural disasters**. 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.

A corollary is that it is possible to reduce the welfare impact of disasters by accelerating reconstruction. The ability to recover and reconstruct rapidly is often referred to as "resilience", and building resilience is one way of reducing the impact of disasters on welfare. Chapter 3 introduces a definition of risk that includes resilience, and Chap. 6 discusses recommendations for risk management "policy mix" that include actions to reduce direct and indirect losses.

As mentioned in Box 2.2, aggregated numbers can hide very large distributive impacts: GDP and aggregated consumption can be misleading instruments to measure actual welfare losses, especially on the poorest. This is particularly important for disasters, as the poorest are usually more exposed and less able to protect themselves and recover from shocks. As already mentioned, Rodriguez-Oreggia et al. (2009) show that municipalities affected by disasters in Mexico see an increase in poverty by 1.5–3.6 % point. Baez and Mason (2008) present evidence for El Salvador, where earthquakes in 2001 reduced income and consumption per capita of the most affected households by one third. Various studies have investigated the 1984/1985 drought in Burkina Faso and find consumption levels reduced by up to 19 % in certain regions (Kazianga and Udry 2006; Fafchamps et al. 1998). These numbers show that the impact on affected households can be much larger than aggregated figures. Chapter 5 shows in a case study on Mumbai how these effects can be investigated, and confirms that aggregated impact analyses are not very useful to assess them. Then Chap. 6 discusses how cost-benefit analyses can account for the impact on poverty, and Chap. 7 shows that alternative decision-making techniques are able to account for poverty impacts directly, through the use of multiple metrics for measuring risk and disaster losses.

[8]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.

2.4 Assessing Disaster Losses

2.4.1 *Measuring Indirect Losses Using Econometric Analyses*

Econometrics analyses have been used to measure output losses, understood as reduction in GDP following a disaster, but they reach contradictory conclusions. Albala-Bertrand (1993) and Skidmore and Toya (2002) suggest that natural disasters have a positive influence on long-term economic growth, probably thanks to both the productivity effect (Sect. 2.2.4) and the stimulus effect of reconstruction (Sect. 2.2.5). Others, like Noy and Nualsri (2007), Noy (2009), Hochrainer (2009), Jaramillo (2009), Raddatz (2009), and Felbermayr and Gröschl (2013) suggest that the overall impact of disasters on growth is negative. At local scale, Strobl (2011) investigates the impact of hurricane landfall on county-level economic growth in the US and shows that a county that is stuck by at least one hurricane over a year sees its economic growth reduced on average by 0.79 percentage point (and increased by only 0.22 percentage point the following year). On Vietnam, Noy and Vu (2009) investigate the impact of disasters on economic growth at the province level, and find that lethal disasters decrease economic production while costly disasters increase short-term growth.

The lack of consensus on the impact of disasters on GDP is likely to arise from different impacts from small and large disasters, the latter having a negative impact on growth while the former enhance growth, and from different impacts from different types of disasters. For instance, Felbermayr and Gröschl (2013) find that disasters in the top decile in terms of magnitude lead on average to a 3 % reduction in GDP growth. The loss is only 1.5 % for disasters in the top 15 % percentile, and 0.8 % for disasters in the top 20 %. For smaller disasters, no impact can be detected. The type of disaster also matters: Loayza et al. (2012) find that droughts reduce GDP growth by 1.7 percentage point, while floods increase GDP by 0.5 % (possibly because floods enrich soils and increase agricultural productivity).

This explanation appears consistent with results from modeling work: small disasters can create a stimulus effect that increases GDP in spite of the destructions; large disasters implies larger losses that cannot be compensated by a stimulus effect (see Sect. 2.2.5). Also, different disasters have different consequences: a drought reduces output without damaging assets, i.e. without creating reconstruction demands that can stimulate the economy.

2.4.2 *Modeling Indirect Losses*

Many scholars have used economic models to estimate output losses. Many different models have been used, but 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. This literature looks at different types of hazards (floods, earthquakes, droughts, or even terrorist attacks). It includes Rose et al. (1997); Haimes and Jiang (2001); Bockarjova et al. (2004); Okuyama (2004); Okuyama et al. (2004); Santos and Haimes (2004); Hallegatte (2008, 2014).

The IO approach is based on the idea that, over the short term, the production system is fixed and that substitution possibilities are inexistent. The IO model is originally a demand-driven model, which can be used to determine how much needs to be produced in each sector to satisfy a given level of final demand (see, e.g., Oosterhaven 1988; Cochrane 2004). A strict implementation of the IO approach implies that the most affected sector would become the bottleneck for the entire economic system, and that the final economic output would be reduced proportionally to the reduction in the most affected sector output. For instance if the plastic production sector experiences a 20 % decrease in production because one factory is damaged, this production loss would propagate into the economic system leading to a 20 % reduction in the final output of all sectors. This is an overestimation of the loss (for instance because it does not account for the fact that some intermediate consumption can be stocked and are not absolutely necessary for other production processes). Moreover, using this approach makes the final result in terms of output loss dependent on the sectoral disaggregation (the economy looks more vulnerable if it is described with many small sectors than with a few large sectors; see also Box 2.4).

This problem arises from the fact that IO models do not include a modeling of how to distribute the production (or the production scarcity after a shock) from one sector to different demands and different sectors. For example, if the plastic production is reduced by 20 %, it does not mean that all users and clients will experience a 20 % reduction in plastic production availability. Maybe some sectors (e.g., the automobile sector) will have access to an unchanged supply of plastic products while other sectors (e.g., the toy production sector) will experience a larger drop in supply. This is why **IO models used to model disasters are adapted to include a modeling of how the production of each sector is distributed across various clients and demands** (Okuyama 2004; Okuyama et al. 2004; Santos and Haimes 2004; Hallegatte 2008, 2014). But in these adjustments, the main assumption of the IO model remains: producing one unit in one sector (e.g., one car) requires a fixed and constant amount of inputs from other sectors (e.g., a given amount of steel, four wheels, etc.).

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 (e.g., Rose and Liao 2005; Rose et al. 2007). In this framework, there is no rationing in the economic system and markets are always perfectly balanced. A disaster-caused destruction of production capital in a sector translates into a reduction in the production of the corresponding commodity, and into an increase in its price. This increase in price leads in turn to a reduction in its consumption, restoring the equality between demand and the reduced production. Moreover, in CGE models based on Cobb-Douglas or Constant Elasticity of Substitution production function, the production technology is not fixed anymore and there is short-term input substitution: in the presence of scarcity in one input, production can be carried out using less of this input, and using more of other inputs. Because of socio-economic inertia, transaction costs and anti-gouging legislation, however, the adjustment through prices appears unlikely in disaster aftermath. In post-disaster situations, little changes in prices have been observed, except in the construction sector. But prices and elasticity in CGE can also be seen as an artificial way of modeling flexibility. In that case, prices in the model should be considered as proxies for scarcity, more than actual observable prices. The CGE-model flexibilities (the signaling effect of prices, reduction in demand, and substitution in the production process) smooth any exogenous shock and mitigate disaster consequences.

Economic losses caused by a disaster are smaller in a CGE setting than in an IO setting. It is often considered that IO models represent the short-term economic dynamics, in which production technologies are fixed and prices cannot adjust. CGE models, on the other hand, represent the long-term dynamics, in which flexibility in production processes and markets allow for an adjustment of the economic system. In reality, it is likely that IO models are pessimistic in their assessment of disaster output losses, because there is flexibility even over the short term (for instance, maintenance can be postponed; workers can do more hours to cope with the shock; production can be rescheduled, see Rose et al. 2007). It is also likely that CGE models are optimistic, even in the long run, because prices have stickiness and cannot adjust perfectly, and because substitution has technical limits that are not always adequately represented in production functions.

Natural disasters and their reconstruction phases are medium-term events, spanning from the first hours of the shock to years of reconstruction after large scale events. Some authors have looked for intermediate approaches to natural disaster modeling, trying to find a common ground between IO and CGE. Rose and Liao (2005) and Rose et al. (2007) use a CGE framework, but with a lower substitution elasticity to take into account the fact that substitution is more limited over the medium term than over the long term. Going in the other direction, other authors developed IO models that answer previous IO-model shortcomings by introducing explicit supply constraints and production flexibility (e.g., Okuyama 2004; Okuyama et al. 2004).

Another difficulty of disaster cost assessment lies in the aggregation level of CGE and IO models, which represent economic sectors, i.e. thousands of businesses located in different places, as a unique producer. In such a framework, all businesses from one sector are assumed to suffer from the same direct impacts from disasters; in other terms, impacts are homogeneously distributed among the businesses from each sector. Also, if one business cannot produce, it is assumed that its production can be replaced by output from any other business of the same sector. These two assumptions are clearly overoptimistic, as they overestimate substitution capacity in the economic system. Taking into account the multiplicity of producing units, their location, and explicit supply-chains with inventories would allow for a much more realistic representation of natural disaster consequences. Haimes and Jiang (2001), Anderson et al. (2007), Battiston et al. (2007), Weisbuch and Battiston (2005), Coluzzi et al. (2010), and Henriet et al. (2012) investigate this issue and propose modeling approaches to account for these effects. But these works remain theoretical and far from any operational use.

Considering the sensitivity of model results to many parameters, and the limitation of existing tools, it is fair to admit that models are useful tools to explore the indirect consequences of disasters but cannot estimate the cost of a disaster. Progress in this domain would be welcome and useful. To do so, much more research should be devoted to this underworked problem.

2.5 Conclusion and the Definition of *Resilience*

This chapter highlights the main difficulties in defining, measuring, and predicting the total cost of disasters. It focuses on indirect (or output) losses, considered as a major component of the total loss of welfare.

The main conclusion is that it is impossible to define "the cost" of a disaster, as the relevant cost depends largely on the purpose of the assessment. The best definition depends on whether the assessment is supposed to inform insurers, cost-benefit analyses of prevention measure, or international aid providers. A first lesson is that any disaster cost assessment should start by stating clearly the purpose of the assessment and the cost definition that is used. Following this recommendation would avoid misleading use of assessments, and improper comparison and aggregation of results. Depending on the purpose of the assessment, the relevant definition of the indirect cost is different, and the most adequate methodology may also change.

In particular, aggregated assessments provide national- or regional-scale assessments that can hide significant impacts on some categories, and especially on the poorest. Beyond aggregated figures, it can therefore be recommended to complement classical economic analyses with targeted studies on how the poor (and other categories particularly exposed to some risk, such as farmers for droughts) are impacted.

Also, the analysis shows that the welfare cost of a disaster does not depend only on the physical characteristics of the event, or on its direct impacts only. 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 *resilience* of the economy to natural disasters, is an important parameter to estimate the overall vulnerability of a population.

To reduce the negative impact on natural disasters on population welfare, the first approach is to reduce the direct impacts on the economic systems, using for instance better coastal protections and stricter building norms. But another approach consist of reducing indirect losses through an increase in the resilience of the socio-economic system, using for instance insurance scheme or government support to the affected population. **An optimal risk management strategy is very likely to include measures targeting direct impacts (disaster risk reduction actions) and measures targeting indirect impacts (resilience building actions)**.

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