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The Economics of Natural Disasters: an overview of the current research issues and methods

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Abstract

In the last decades, we have observed a dramatic increase in the number of reported natural disasters and of their widespread human, economic, and environmental losses. This paper presents an overview of the current status of economic research on natural disasters. Firstly, it discusses key issues related to disaster definition, available datasets, and cost assessment. Then, it presents the main methodological approaches for estimating impacts and effects of natural disasters on the economy. Finally, it proposes a number of possible future research directions.

Keywords: definitions, data bias, true cost assessment, theoretical empirical and simulation models.

JEL classification: A12, C8, E1, O1, O40, Q54

1. Introduction

Natural disasters and catastrophes, with their associated human and economic losses, have always been one of mankind's major fears and fascinations. However, until the 1990's, research related to the economics of their impact and consequences has been limited (Okuyama, 2009; Cavallo & Noy, 2011). Since then, a surge of large-scale devastating events such as the Kobe Earthquake (1995), the Indian Ocean Tsunami (2004), Hurricane Katrina (2005), the Haitian Earthquake (2010), and the Japanese Tsunami (2011) has prompted the international community to give more attention to this topic and has instilled the fear that disasters are becoming more frequent and severe. Indeed, both the number of reported natural disasters and their associated losses have increased dramatically in the last century, and this trend has not changed (Guha-Sapir *et al.*, 2004). Whether and to what extent this trend is natural or due to human and societal factors, is one of the several research questions that economists are focusing on at present (see e.g., Strömberg, 2007; Kellenberg & Mobarak, 2011).

Since the seminal work of Dacy and Kunreuther (1969) the economic literature on natural disasters has grown considerably. However, the main review papers, e.g., Yezer (2002), Okuyama (2009), Hallegatte and Przyluski (2010), Kellenberg and Mobarak (2011), Cavallo and Noy (2011), show heterogeneity and indicate a lack of consensus among researchers. There are indeed several issues that future research must address more thoroughly in order to consolidate this flourishing field. In particular, most papers 1) do not clearly define the boundaries of the object discussed and use ambiguous terminology; 2) do not sufficiently consider the fundamental problem of the quality of existing datasets and how this can affect the results; 3) do not consider ideas and methods that have been developed in other strands of literature, especially regarding how to assess the "true" cost of a disaster. Moreover, with the exception of some studies on large-scale environmental catastrophes, there are very few theoretical works on the effects of natural disasters on economic dynamics. Current research tends to focus on various empirical methods, apparently with minimal communication between the different approaches.

Although the problems and methods discussed in this paper are not new per se, they have not been presented in the literature in an organic and coherent way. Existing reviews may describe several of these topics in more detail, but they focus only on some of them, not giving the whole picture. The economics of natural disasters, however, is a complex and multifaceted subject that cannot be understood by only looking at some parts. Therefore, the purpose of this paper is to present an informative general overview of the current fundamental issues and methodological approaches employed in this field, with a broader scope than that of currently available reviews. This is expected to be especially useful for persons coming from related, but different, research areas and thus unfamiliar with this subject. Furthermore, the framework adopted here is new and more organic, because the various methods are grouped according to three general approaches, identified as a *theoretical approach*, an *empirical approach*, and a *simulation approach*. This organizing system is important because it helps identify the main aspects of economic research on natural disasters: identifying the underlying dynamics, providing estimates of the magnitude and importance of their impacts, and allowing one to predict their effects. Finally, this paper has also the objective of outlining a number of possible future research directions that arise from the key issues discussed.

The paper is structured as follows. Section 2 contextualizes the economics of natural disasters in the broader view of social science disaster studies. Section 3 discusses three fundamental issues that researchers have to deal with: (3.1) defining what a “disaster” is; (3.2) problems of available datasets; and (3.3) assessing disaster costs. Section 4 presents the main methodological approaches employed to study the economic effects of natural disasters: (4.1) theoretical; (4.2) empirical; and (4.3) numerical simulation. Section 5 suggests directions for future research. Section 6 summarizes and concludes.

2. A broader picture: connections with other social sciences

Most authors do not define what a disaster is, considering the concept implicit. This is a source of ambiguity that aggravates the problem of the lack of standards and homogeneity in the literature. However, many issues addressed in economic research on natural disasters are in fact very general and go beyond Economics itself. Therefore, before attempting to give specific definitions and restricting the scope to Economics, it is useful to have a quick look at the broader picture offered by social science literature on natural disasters and catastrophes. This helps to understand the choice of definitions made in Section 3, to contextualize the issues that will be discussed later, and to see the links between Economics and other disciplines. Indeed, natural disasters are complex events that cannot be fully understood without taking into account their transdisciplinary character.

In this section a few examples of wide-ranging social science books discussing fundamental issues that are also relevant for the economics literature will be briefly presented. However, a comprehensive overview of Disaster Studies can be found in a recent textbook labelled “Disaster Theory: An Interdisciplinary Approach to Concepts and Causes” (Etkin, 2015).

"What Is A Disaster? New Answers to Old Questions" (Perry and Quarantelli, 2005) is devoted to the very question of what constitutes a disaster. Indeed, even when the underlying natural hazard is very clear, defining an event as a disaster depends on the context and there is no general accepted definition of the term “disaster” itself. For this reason there is no standard rule regarding which events should be included in disaster data sets, which as a result are difficult to compare (Tschoegl *et al.*, 2006).

"Catastrophe: Risk and Response" (Posner, 2004) warns about the importance of not underestimating catastrophic risks, even though the probabilities involved are very small. The author’s concern is well posed, since there is evidence (Kunreuther, 1996) that even in areas subject to high natural hazard risk property owners tend to ignore it and underinvest in insurance and mitigation efforts.

"At Risk: natural hazards, people’s vulnerability and disasters" (Wisner, Blaikie, Cannon and Davis, 2003) explains very well the problems of *exposure* and *vulnerability* and how they can greatly affect the outcome of a natural hazard event. Despite the name “natural” disasters, what really matters is the socio-economic fabric of the affected population (Toya & Skidmore, 2007).

“Geographical Information Systems in Assessing Natural Hazards” (Carrara, A., & Guzzetti, F. (Eds.), 2013) addresses the problem of the spatial and temporal heterogeneity inherent in natural hazards and human vulnerability. This is very important when estimating or assessing disaster losses and indeed many

government and private organizations employ Geographical Information Systems (GIS)-based models (see Section 4.2).

Finally, a peculiar book written from an Ecology perspective but with a general and counter-intuitive message is: "The silver lining: the benefits of natural disasters" by S.R. Reice (2003). The author argues that the traditional paradigm of considering a system in equilibrium as an optimal situation may be flawed. Indeed, sudden and sweeping disturbances such as natural disasters could help an ecosystem to perform tasks that are fundamental for its well-functioning and thus are beneficial. A similar idea, called “creative (or Schumpeterian) destruction” [1] has been debated in Economics for decades (see e.g. Cuaresma, Hlouskova, & Obersteiner, 2008; Leiter, Oberhofer, & Raschky, 2009).

3. Fundamental issues

Examining the economic literature on natural disasters, some important problems emerge. In particular, this paper identifies three fundamental issues that future research must address more seriously: the lack of standard definitions and terminology, the problem of available data quality, and the challenge of assessing the “true” cost of a disaster.

3.1. Definitions of disaster

a) General definitions

In clarifying the definition of natural disaster, a great contribution comes from the social science of Disaster Studies, where this issue has been largely debated (Lindell, 2013; Etkin, 2015). Whether an event is called a disaster or something else greatly depends on the social context, the temporal and spatial scale, the size and type of damages. Thus, a single all-encompassing definition is impossible and some scholars as S. Cutter even argue whether having a definition of “disaster” is worthwhile (Perry and Quarantelli, 2005). Other scholars as Perry and Quarantelli (2005), instead, believe that such theoretical questions are important. They explain that *emergencies*, *disasters*, and *catastrophes* are different phenomena and

[1] For an introduction to this concept, see e.g. https://en.wikipedia.org/wiki/Creative_destruction

categorize them according to organizational and sociological criteria. This is in line with the general definitions employed by national and international authorities and NGOs. For example, according to the United Nations Office for Disaster Risk Reduction (UNISDR) a disaster is *"A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources*" (https://www.unisdr.org/we/inform/terminology). General definitions are necessarily vague in regards to the size and type of losses. However, what determines the disaster is that the routine life of a community is disrupted and local resources are not sufficient for response and recovery[2]. What is considered a "local community" is not explained, but from the literature it seems to be intended at town or county level.

The UNISDR definition does not distinguish between "disaster" and "catastrophe", an ambiguity that is pervasive in the literature. A useful clarification can be found in Posner (2004, p.6): a catastrophe is *"an event that is believed to have a very low probability of materializing but that if it does materialize will produce a harm so great and sudden as to seem discontinuous with the flow of events that preceded it."* A catastrophe, thus, is a disaster such that returning to the previous socio-economic and/or environmental condition is impossible. A typical example is the case of an abrupt and irreversible climate change, where, if the mean global temperature goes over a certain threshold, there will be substantially large and permanent negative changes in the Earth ecosystem and to human society. In this regard, the economic literature is quite rich[3].

This paper mainly discusses disasters that are not catastrophes and that are "natural". In general, disasters are composite events originating from a combination of natural hazards and human actions; therefore, making a distinction between natural (or "acts of God[4]") and man-made disasters is often irrelevant. However, for theoretical purposes, it is useful to distinguish between disasters that have prevalently an exogenous trigger (a natural hazard) and those that are triggered by

[2] Definitions of "response" and "recovery" can be also found on the UNISDR terminology web page.
[3] See e.g. the "Stern Review" (Stern, 2007) and the subsequent literature that spurred from it.
[4] "Act of God" is the legal term used in the English–speaking countries for events outside human control, such that damage liability cannot be attributed to any person (https://en.wikipedia.org/wiki/Act_of_God).

endogenous complex social relations (e.g. pollution, financial crisis, wars, terrorism). Another difference that has to be clear is that between the terms *natural hazard* and *natural disaster*. The former term relates only to the occurrence of the physical event, while the latter refers to its consequence, given the underlying socioeconomic conditions of the affected population. In fact, as explained by several authors (e.g. Strömberg, 2007) a natural disaster is constituted by three factors: the *natural hazard* that acts as a trigger; the number of people and assets that can be affected (*exposure*); and their susceptibility to damage (*vulnerability*). This distinction is especially important for empirical research, because damages and losses can be increased either by increasing the number of hazards, the size of exposure, or the level of vulnerability.

b) Economic definitions

Hallegatte and Przyluski (2010, p.2) state that *"There is no single definition of a disaster. From an economic perspective, however, 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."* In addition, several authors make a distinction between "small" and "large" disasters, meaning shocks to the economy that are *marginal* and *non-marginal*, respectively. This distinction is important because the two cases are fundamentally different (Martin & Pindick, 2015). Another important issue is understanding what is meant by words such as "assets", "production factors", etc. Most authors refer only to the marked-priced ones. However, the functioning of the economic system also depends on non-priced "goods" such as public infrastructures, human and social capital, and natural ecosystems, whose loss is more difficult to evaluate. Determining the impact of a disaster is, therefore, problematic (see Section 4).

This definition indicates how the economic perspective, although closely related to the more sociological one of the UNISDR, differs from it. The focus here is not on the disruption caused to the society, but on the change (temporary or not) to its welfare. However, such a definition is too general for practical purposes. Different research goals and scopes, indeed, require the use of different specific definitions. Usually, in an economic model, a disaster is defined as a change in the value of a variable or a function representing a flow or a stock of wealth, but the exact choice depends on the purpose of the model. Moreover, if the model has to be tested empirically, a quantitative definition is needed.

c) Quantitative definitions

In empirical terms, a disaster is usually defined according to the size of its losses. In order to do so, quantitative definitions are formulated based on objectively measurable criteria. If an event meets these criteria, then it is labelled as “disaster” and recorded in a database.

As an example, the definition for data to be entered into the Emergency Events Database (EM-DAT) (http://www.emdat.be) is that at least one of the following conditions be met:

- 10 or more people killed
- 100 or more people affected
- A state of emergency declared
- International assistance called

Note how the last two criteria relate to the inability condition of the local population to respond with its own resources, as in the UNISDR definition. Notable also is the absence, in EM-DAT, of any criterion regarding monetary losses, which are, instead, included by other databases such as those maintained by reinsurance companies. The fact that each database owner might choose different entry criteria and classification categories usually results in a mismatch between databases, where the same event might be reported or not, or even generate several entries. The main issue in this regard is the “threshold problem”, i.e. how sensible is the definition to a change of the cut-off point that determines what is recorded in the database and what is not (this problem is discussed in detail in Section 3.2).

3.2. The “database problem”

A fundamental problem is that of data availability and quality. Examining various databases, it appears that there are differences in definitions, classification, geographical and temporal resolution, methodology, and sources. Comparing data and deriving statistical inference is thus very difficult.

a) Disaster databases and biases

The only global disaster database openly available is 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. The other two global disaster databases, NatCat and Sigma, are maintained by reinsurance companies (MunichRE and SwissRE, respectively) and hence offer only limited access. In addition to these, several other databases exist, but with limited spatial coverage or focused only on specific disaster types. The most complete review of existing databases, which categorizes them by scope (global, regional, national, or event-based), is the one compiled in 2006 by CRED for the ProVention Consortium (Tschoegl *et al.*, 2006).

The quantity and quality of disaster data varies across several dimensions, including time, space, income levels, and political openness. According to Strömberg (2007), data are more complete in later years and in more developed countries, while data from poorer countries and nondemocratic regimes tend to be less complete or underreported. Cavallo and Noy (2011) also note that the losses reported in the main databases consist only of direct damages and that they are heterogeneous across countries. Again, they found that variability is smaller in developed countries and larger in developing ones.

The database scope and methodology are also a source of bias. For example, while NatCat entries are geocoded, EM-DAT records disasters only at country level and Sigma by event. Most databases, also, limit the duration of a disaster to one year. However, a disaster event can span over several countries (e.g. hurricanes), have a long duration (e.g. droughts), or occur in combination with other disasters (e.g. earthquakes and tsunamis). This means that a single event can generate multiple entries in the data set, or be only partially accounted for. Therefore it is often difficult to determine what damage should be attributed to each specific event

Another problem that deserves particular attention is the *threshold bias*. Setting entry criteria on the number of people killed or affected is intended to make sure that only "relevant" events are recorded as disasters. However, what is considered relevant highly depends on the database owner, its purpose, and scope. For example, disasters of small economic magnitude tend to be underreported in large global databases (which have higher thresholds) compared to small local ones. However, during years with little or no major disaster, the accumulation of frequent small losses might result in the local databases reporting higher figures (Gall, Borden, and Cutter, 2009). Moreover, thresholds are extremely sensitive to population exposure and vulnerability: the more people live in a risk prone area, or the more people are unable (e.g. because of poverty) to cope with an extreme event, the more likely the thresholds conditions will be met, hence increasing the number of recorded disasters in that area.

A detailed discussion of the major biases present in current disaster data sets can be found in Gall, Borden, and Cutter (2009). The authors identify six different types of biases (hazard bias, temporal bias, threshold bias, accounting bias, geographic bias, systemic bias) and carry out a comparative review of four large databases (EM-DAT, NATHAN, SHELDUS, Storm Events) to illustrate their effects.

b) Are disasters becoming more frequent and severe?

As mentioned in the introduction, the number of reported natural disasters has increased dramatically in the last century and this trend is still ongoing. Looking at the data sets recorded in EM-DAT, this increase is particularly sharp in the last four decades. In fact, the recent increase in natural disasters seems to be driven mainly by improved reporting of small disasters, since the frequency of large disasters (which are rare) has not changed significantly over time. This may be due to several reasons, such as the availability of better recording technologies, methods, and coverage by insurance companies and government or international institutions (Guha-Sapir *et al.*, 2004). However, the higher incidence of small disasters in the datasets can also be attributed to changes in the definition of what constitutes a disaster, i.e. the database thresholds may have been lowered (Cavallo & Noy 2011).

Not only the frequency, but also the economic impact of natural disasters seems to be increasing over time. According to Smith and Katz (2013), aggregate losses for weather and climate disasters show an increasing trend due to a significant increasing trend in the frequency of large (billion-dollar) disasters, which they quantify as 5% per year. However, they note that the dataset they use (the US Billion-Dollar Weather/Climate Disaster dataset) is only adjusted for inflation over time (through the CPI), but not for other significant factors such as exposure due to population and wealth growth or demographic shifts.

3.3. The assessment problem: what is the cost of a disaster?

Since economic structures around the globe have become more complex and intertwined, some authors call for the implementation of international standards in order to make cross-country analyses (Okuyama, 2009). Though we are still far from this goal, recently international institutions and governments have shown an interest in this direction, as it is testified by the adoption of the United Nations Sendai Framework for Disaster Risk Reduction in 2015.

In theory, in order to assess the cost of a disaster, all its impacts (damages and losses) have to be correctly identified, evaluated, and summed up. In practice, this is highly problematic. First, some impacts are difficult to identify due to the inherent complexity of a disaster event and its dependence on the space, time, and social context. This is the case, for example, of certain climatological disasters such as droughts. Since they build up slowly over a prolonged period of time, do not have well-defined spatial boundaries, and might cause limited material damages, but long-ranging effects, deciding which losses are attributable to them and which not is rather subjective. Second, even when easily identifiable, some impacts are problematic to evaluate in economic terms, e.g. the loss of human lives or of a natural ecosystem. Third, the choice (or availability) of the instruments and methodologies used for accounting might lead to biased estimates or double-counting.

a) Classification of impacts

Although there are no internationally recognized standards for disaster impact assessment, a very important step was done in 2003 by the Economic Commission for Latin American and the Caribbean with the release of the *Handbook for Estimating the Socio-Economic and Environmental effects of Disasters* (ECLAC, 2003). The ECLAC handbook proposes the following classification of disaster impacts, which reflects the terminology used by most authors: *"a disaster affects assets (direct damages); the flow for the production of goods and services (indirect losses); and the performance of the main macroeconomic aggregates of the affected country (macroeconomic effects)."* (ECLAC, 2003, p.9). Furthermore, direct damages and indirect losses can be differentiated into those related to goods and services that are market-priced (*market losses)* and those for which a price cannot be easily derived (*non-market losses)*[5]. Therefore, the disaster's physical destruction of buildings and goods is an example of market direct damages, while loss of human lives and natural ecosystems are non-market direct damages. Similarly, diminished industrial output and impoverishment of health conditions are examples of market and non-market indirect losses, respectively. However, other authors consider also output losses or business interruptions that are immediate consequence of the disaster as "direct" and only subsequent losses as "indirect". Finally, macroeconomic effects are aggregated effects of the disaster on the economy as a whole that derives from both direct damages and indirect losses. Thus they are not additional losses, but rather represent a complementary way to assess losses from a different perspective (ECLAC, 2003, p.15).

b) The accounting problem

Assessment of damages and losses has to be carried out especially carefully to avoid double-counting or miscounting. In particular, according to standard economic theory, the value of an asset is the net present value of its expected future income flow. Hence, adding the loss of output derived from the destruction of a physical asset is double-counting. However, it can be argued that this rule is valid only under certain assumptions (e.g. the economy is in equilibrium) that might not be true in the immediate aftermath of a disaster event (Hallegatte & Przyluski, 2010).

c) Assessment of direct damages

Direct disaster damages and losses are usually assessed on the basis of data collected on specific disaster events from various sources in order to produce impact reports used by governments, NGOs, and insurance companies to deal with the aftermath of the disaster and to prepare for future similar ones. Several methodologies are employed, both because each hazard type is different and because definitions of damages and losses are different across countries. For example, Smith and Katz (2013) describe the methodology applied by the US Billion-Dollar Weather/Climate Disaster report to quantify economic losses from weather and climate disasters since 1980. This method is based on direct insured losses and it is called "factor approach" because such losses are converted into total (direct) losses by multiplying them by a simple factor, which differs according to disaster type

[5] The ECLAC uses the terms *tangible* and *intangible* losses, other authors *economic* and *non-economic* losses.

and data source. Note that the billion-dollar dataset does not include indirect losses of any kind, a limitation that is common to many datasets. Several sources are considered and data from private insurance companies are complemented by data from public disaster relief agencies whenever a situation of underinsurance is suspected. The results, however, are clearly affected by the level of *insurance penetration* (i.e. the rate of insured versus total losses), which in developing countries is usually very low and thus can lead to large underestimations of the disaster costs.

d) Estimation of indirect losses

This kind of losses can be estimated through various empirical (e.g. econometric analysis) and simulation (e.g. computable general equilibrium models) methods, (see Section 4.3). A significant number of these works attempts to estimate the indirect impact of disasters on economic growth. However, an important note has to be made on the metric used to measure growth. Most studies focus on GDP, but is this the right measure? Looking at national accounts, there is a clear increase in GDP in the aftermath of a disaster because the economy is boosted by reconstruction activities. However, GDP does not take into account the depletion of natural resources that have been destroyed by the disaster[6] or have been used up for reconstruction. In fact, GDP records economic flows (e.g. income derived from production activities), but does not consider what happens to the underlying stocks (e.g. minerals, oil, natural forests, marine resources). Depletion or overexploitation of natural assets could lead to an overall decrease of a country's wealth even to the point of hindering its future growth (NCC First Report, 2013, p.40). Therefore, other measures that include stocks depreciation, such as NDP, may be preferable for the analysis of the economic effects of natural disasters. Although this problem has been addressed in the environmental economic literature (see, e.g., Dasgupta & Mäler, 2000; Barbier, 2013), there is not much discussion of it in the disaster literature. Finally, aggregate measures such as GDP do not capture the distribution of growth and thus cannot reflect inequality aspects. However, income inequality is important in determining the levels of resilience of different groups of people, as those with less income have fewer resources to cope with the disaster effects (Kahn, 2005).

e) Estimation of non-market losses

[6] With the exception of timber resources from commercial forests, which are accounted for.

Only few studies attempt to estimate the non-market losses caused by natural disasters. Although the task is not easy, methods to do so are well-known in the environmental and in the valuation literature (e.g. the classical work of Thaler & Rosen, 1976, on “the value of saving a life”). It is thus surprising that this issue has received such a scarce attention by the disaster literature, with some notable exceptions such as Johansson and Kriström (2015). They include in their dynamic Cost-Benefit Analysis model not only loss of private assets, but also of public goods (such as infrastructure), as well as the cost of statistical lives lost. The difference in the cost estimates obtained with this approach compared to the usual ones is particularly evident for disasters that result in many deaths, but have relatively low reported economic losses.

4. Economic approaches and methods

There are a few excellent reviews that cover several of the topics presented here in more detail or provid more references, e.g., Okuyama (2009), Hallegatte and Przyluski (2010), Kellenberg and Mobarak (2011), Cavallo and Noy (2011). However, the author is not aware of any review that describes all the different methods presented in this paper, since existing reviews usually focus only on some of them. Furthermore, the framework adopted here is new because the various methods are grouped according to three general approaches, which are identified as a *theoretical approach*, an *empirical approach*, and a *simulation approach*. Although different methods can shed some light on the problem, organizing them into these three different but complementary categories helps reach a synthetic view of the problem. Theory helps identify the underlying economic dynamics of disaster situations, empirical analysis provides estimates of the magnitude and importance of their impacts, numeric simulations allow one to predict their effects. The purpose of this section, therefore, is not to be exhaustive, but to give an organic and informative general picture of the main approaches and methods used in economic research to study natural disasters.

4.1. Theoretical approach

In general, natural disasters can be viewed as mostly exogenous shocks that affect the (macro)economic cycle and, as such, they can be described within the standard neoclassical General Equilibrium theory. Therefore, it seems reasonable to adopt a macroeconomic model that can also include microeconomic variables and stochastic aspects, but other modelling approaches have also been attempted in the literature.

a) Catastrophe models

Climate change or environmental pollution catastrophe models are a whole field of literature in itself and are outside the scope of this paper, but it is worth mentioning them because some of these models may probably be adapted to natural disasters as well (e.g. Polasky, de Zeeuw, & Wagener, 2011; De Zeeuw & Zemel, 2012; Lemoine & Traeger, 2014). A similar reasoning could be used for some man-made or economic catastrophes models (e.g. Aronsson, Backlund and Löfgren, 1998; Barro, 2009). However, ordinary "small" disasters present different theoretical characteristics than rare and large-scale disasters/catastrophes and thus it is necessary to be very careful on the assumptions and implications of these models. In particular, catastrophe models normally assume a permanent regime shift after the disaster: the production function or the total factor productivity (i.e. the technology) changes forever onwards. Instead, ordinary disasters are followed by a recovery period after which the economy goes back to the trend that would have prevailed if the event did not occur. Martin and Pindick (2014), for example, point out that standard CBA (cost-benefit analysis) works well when evaluating the costs and benefits of avoiding disasters that are relatively small compared to the size of the whole economy (and not too frequent), because their impact is "marginal" and do not alter substantially society's aggregate consumption. However, when the size of the disasters is large in relation to the economy[7], as in the case of global catastrophes, there is an essential interdependence among the policies that can be taken to cope with them and therefore it is not possible to evaluate them in isolation.

b) Natural disaster models

Purely theoretical models for ordinary disasters, such as earthquakes and hurricanes, are very scarce in the literature. An early attempt is that of Yezer and Rubin (1987), who proposed a theoretical model of local economic effects of natural disasters based on a "geometric model for analysis of urban effects" on the housing

[7] Or when they are small but very frequent, so that their aggregate impact is large.

and land markets. It is a spatial model where agents' willingness to pay for land depend on the location (from the city center to the countryside). In this framework, a natural disaster is seen as a "negative natural resource" that tends to decrease the productivity of capital and labor in the location where it occurs. However, most subsequent theoretical models follow a completely different approach, based on growth equations. Probably one of the first (and few) macroeconomic theoretical models specifically designed to study natural disasters effects on growth is that of Albala-Bertrand (1993a). It is a complex model that divides a "disaster situation" into three different analytical components (impact, response, interference), distinguishes between direct (stock) and indirect (flow) effects, and also distinguishes between disaster sizes.

Simple growth models (like the Solow-Swan model) are the ones usually employed as a framework for econometric analysis (e.g. Skidmore & Toya, 2002), while more complex CGE (computable general equilibrium) models are used as framework for simulation studies (e.g. Hallegatte, 2008; Rose & Liao, 2005). However, in these cases, the theory provides only a context for the empirical/simulation analyses, it does not provide specific predictions or explanations.

c) Other models

A distinct model is that of Johannsson and Kriström (2015). It is a Ramsey-type model with a stochastic component that tries to achieve a better description of the *true* cost of a disaster by including not only loss of private assets, but also of public goods (such as infrastructures), as well as the cost of statistical lives lost.

Finally, there are also hybrid models, where economic models are combined with engineering, or meteorological, or biological models. One example is that of Holden and Shiferaw (2004), who develop a dynamic biophysical agroeconomic model to study the impact of draught in a severely degraded crop-livestock farming system in Ethiopia. The model optimizes household production and consumption over a limited time horizon.

4.2. Empirical approach

a) Risk Assessment

Data collected from past disaster events can be used to perform risk assessments to estimate possible future losses in a particular area. This knowledge is further employed to devise financial and regulatory risk mitigation strategies, in particular insurance policies and building codes.

Risk Assessment is the determination of estimates of the *risk* associated with a certain hazard. Quantitative risk assessment requires identifying and quantifying two components: the magnitude of *potential loss*, and the *probability* of its occurrence. Then the *total risk* R can be defined as the sum of individual risks R_i, computed as the product of potential losses L_i and their probabilities $p(L_i)$: $R = \sum_i L_i p(L_i)$ [8].

The main difficulty in such estimation is that either L or p or both can be subject to a high degree of uncertainty and different stakeholders may have different subjective perceptions of these uncertainties, especially regarding probability. Moreover, even though the same value of R could be computed either from a situation of low potential loss and high probability of occurrence or vice versa, these two cases present different characteristics and thus are usually treated differently. Frequently occurring disasters (e.g. wild fires) make it possible to estimate risks rather precisely, while rare but catastrophic disasters (e.g. hurricanes, earthquakes) present more challenges because of the scarce availability of past data. Because of these problems, for example, insurance companies usually refuse to insure against hurricanes and earthquakes and whenever they do, they charge higher premiums than for equally risky but more understood hazards.

Nowadays the determination of potential losses and associated risks is facilitated by the use of complex *catastrophe modelling* software, usually built on GIS (Geographic Information System) technology, which employ updated detailed information on vulnerable assets in hazard-prone areas coupled with probabilistic models (different for each type of hazard). The most widely used is HAZUS[9], originally released by the US Federal Emergency Management Agency (FEMA) in 1997, and currently capable of handling four types of hazards: flooding, hurricanes, coastal surges, and earthquakes. The methodology on which HAZUS is based is described in Cochrane, Chang, and Rose (1997). In short, HAZUS estimates the risk in three steps. First, it

[8] See "Risk Assessment" in *Wikipedia*: https://en.wikipedia.org/wiki/Risk_assessment

[9] See http://www.fema.gov/hazus

calculates the exposure in a certain area. Second, it characterizes the level of hazard in that area. Third, it uses exposure and hazard level to estimate potential losses. These results are then used by government planners, emergency managers and insurance companies to devise optimal mitigation strategies.

Mitigation of disaster losses is a difficult enterprise. This is primarily due to what Kunreuther calls “the natural disaster syndrome”: “It consists of two interrelated components: limited interest in protection prior to a disaster, and high cost to insurers and federal government following a catastrophic event.” (Kunreuther, 1996, p.171). In particular, preferences for purchasing (or not) insurance are dependent on subjective risk perceptions (Kunreuther & Pauly, 2009; Petrolia, Landry, & Coble, 2013). That on risk insurance is a well-developed strand of economic literature; a review can be found, e.g., in Kunreuther and Michel-Kerjan (2014).

b) The macroeconomic perspective: econometric analysis

Econometric models are based on statistics and in most cases, do not focus on a single event, but investigate the mean effects of a series of similar events over time.

There is a fairly large literature that employs econometric analysis to study the economic impact of natural disasters. It is possible to divide this literature in two main categories:

1) studies that attempt to identify the main determinants of a disaster (direct losses) and to estimate their relative impact;
2) studies that try to estimate the (indirect) effects of natural disasters, especially on economic growth[10].

Determinants of direct losses

Econometric analysis can be employed to identify and study the main determinants of disaster direct losses and estimate their impact. In general, most works use panel data to estimate a model of the form:

$$D_{it} = \alpha + \beta \boldsymbol{X}_{it} + \varepsilon_{it}$$

[10] Most studies of this type, indeed, focus on GDP growth. However, there are also a few studies, such as Rodriguez-Oreggia *et al.* (2013), that examine effects on human development and poverty.

where D_{it} is a measure of direct damages (e.g. number of deaths or asset losses) of a disaster occurred in country i at time t. Note that most studies focus only on a certain disaster type (e.g. earthquakes, hurricanes), or typology (e.g. hydrological, climatological). Indeed, since different natural hazards are triggered by different factors and also their impacts may be very heterogeneous, aggregating every type of disaster is usually meaningless. Therefore, each paper proposes a vector of control variables $\boldsymbol{X}_{it}$ specific for the disaster type in analysis. These usually include some measure of the disaster *physical intensity* (Richter scale magnitude for earthquakes, wind speed for hurricanes, etc.) and some measure of the affected country *vulnerability*, i.e. factors that make a country more susceptible to negative impacts than another (e.g. human or economic development level). Finally, the model includes also an error term ε_{it} that is typically assumed to be independent and identically distributed (see e.g., Cavallo and Noy, 2011).

While the susceptibility of a country to natural hazards is mainly due to its geographical conditions, about which of course not much can be done, the literature has identified a number of factors affecting vulnerability that depend on economic, social, and political conditions, which therefore can be mitigated by policy actions.

The first is the level of development. As shown by several studies (e.g. Kahn, 2005; Jaramillo, 2009) richer and more advanced countries suffer fewer losses from natural disasters than developing countries, most likely because they can afford to spend more resources, and more efficiently, on mitigation efforts (e.g. more resilient buildings and infrastructures). The relationship between economic development and vulnerability needs not be linear. In fact, Kellenberg and Mobarak (2008) argue that it follows an inverted U shape: initially an increase in wealth may encourage people to relocate to more desirable but more dangerous locations such as coastal areas or flood plains, while only a further increase would allow them to purchase mitigation measures.

The second main determinant is the country size. The larger a country is in terms of population, land area, GDP, the more is its *exposure* to direct damages from natural disasters. However, bigger countries are generally more resilient because they are capable to mobilize more resources for mitigation and, being more diversified, can more easily absorb economic shocks. Therefore, larger countries usually have larger direct damages in absolute terms, but lower in relation to their size.

The third most important factor is the level of political and institutional maturity. The literature agrees that more democratic and/or institutionally stable regimes are able to better prevent or mitigate disaster impacts (Kahn, 2005; Skidmore & Toya, 2007; Strömberg, 2007). Among various reasons, a notable one is that in mature democracies politicians and governments are more accountable for the efficacy of prevention/mitigation policies and thus pursue them more actively.

Effects on growth

After the initial direct impact, natural disasters also have indirect consequences on the economy in the aftermath (e.g. effects on production, consumption, income, employment). The time horizon considered by the analysis is of fundamental importance. As noted both by Okuyama (2009) and Cavallo and Noy (2011), research on long-term effects of disasters on economic growth is very limited and often inconclusive. This is due to many reasons, such as the difficulty of constructing appropriate counterfactuals and the complexity of assessing the impact of human capital losses or of negative externalities. For example, in the context of developing countries, replacing lost human capital often proves very difficult and therefore "long-range effects of disaster situation do not primarily depend on disaster loss but on its interference with ongoing social dynamics" (Albala-Bertrand, 1993, p.204). Moreover, long-run effects are inherently difficult to extrapolate from the data because the presence of in-built social mechanisms of resilience and adaptation counteracts most potential higher-order effects (i.e. during a crisis firms and communities change their behaviour and manage their resources differently to better cope with the disaster consequences).

Most macroeconomics research which employs econometric analysis focus on short-run economic growth and (per capita) GDP is the typically chosen measure. Thus, most studies propose a model of the form:

$$Y_{it} = \alpha + \beta \boldsymbol{X}_{it} + \gamma D_{it} + \varepsilon_{it}$$

where the dependent variable Y_{it} is country i per capita GDP in year t, $\boldsymbol{X}_{it}$ is a vector of control variables (usually including $Y_{i,t-1}$), D_{it} is a measure of the direct disaster impact (or, sometimes, an indicator variable of disaster occurrence), and ε_{it} is the usual error term. This basic econometric model can be extended to include interaction variables or can be adapted to analyze impacts on specific economic sectors (see e.g., Cavallo and Noy, 2011).

Some studies, in particular Albala-Bertrand (1993) and Skidmore and Toya (2002), found that disasters have some *positive effect* on growth. This result can be explained by both the "stimulus effect" and "productivity effect" (also known as Schumpeterian creative destruction). The first happens because the increase in demand for the goods needed in the reconstruction phase may stimulate the economic activity in the region. The second is due to the fact that destroyed productive capital may be replaced with new assets that embody the most recent technologies, which thus will lead to a higher productivity. Cuaresma *et al* (2008, p.10) claim that there is, indeed, "strong evidence concerning the fact that natural disasters do serve as creative destruction". However, these effects may not work. Reconstruction can stimulate economic activity only if the pre-disaster economy was depressed, otherwise the negative effects outweigh the positive ones. Destroyed capital is, in fact, rarely replaced by a more advanced one, because usually it takes time to adapt to new technologies, while producers usually have to restore their business activity as soon as possible (See Hallegatte & Przyluski (2010) for a detailed explanation of these two effects). Indeed, many recent studies (e.g. Noy & Nualsri, 2007; Jaramillo, 2009; Raddatz, 2009) found that the effects of natural disasters on economic growth are mixed, but *overall negative*. This seems to be the emerging consensus in the literature (Cavallo & Noy 2011).

Some studies, instead, seem to suggest that natural disasters may actually have *differential effects* on growth. For example, according to Leiter *et al.* (2009), this could depend on the share of intangible assets held by affected firms. Loyaza *et al.* (2009) argue that small and large disasters may have opposite effects (enhancing or depressing growth).

4.3. Simulation approach

Econometric models are statistically rigorous and can provide stochastic estimates, useful for forecast analysis. However, they do require large time series datasets and cannot easily distinguish between direct and indirect (higher order) effects, giving an estimate of the aggregate total impact. Since researchers and policy makers are often interested to know the indirect impact of a disaster on the economic system through its interindustry relationships, various other modelling frameworks have been employed for this task; in particular, Input-Output (IO) and Computable General Equilibrium (CGE) models.

a) Input-Output (IO) models

Briefly, an IO model is based on a matrix in which each column shows the value of inputs to each sector and each row represents the value of each sector's outputs. A natural disaster can be seen as an exogenous shock that reduces the available inputs, usually resulting in changes in production and consumption patterns.

Understanding the flexibility of the production system to substitute for temporary unavailable inputs and its adaptability to absorb shocks is a complex and still largely unknown matter, to which researchers have been dedicating more and more interest (Okuyama, 2009; Hallegatte & Przyluski, 2010).

The considered timescale plays a fundamental role. In the short term, the production system can be considered fixed, because it takes time to replace machinery, build new factories, train new labour, etc. Therefore, local production capacity is highly constrained and only imports from outside the affected region can provide some flexibility. This is the picture of the economic system portrayed in IO models, in which each input is produced using a fixed number of inputs in fixed proportions. These modeling approaches also allow for a clear distinction of direct and indirect impacts. The use of IO models for evaluating disaster impacts have been pioneered by Cochrane (1974) and since then they have been largely employed in this line of literature (see e.g., Okuyama 2009).

b) Computable General Equilibrium (CGE) models

A CGE is more complex than an IO model. It consists of two parts: a database and a set of equations. The database contains of a table of coefficients, usually in the form of a Social Accounting Matrix[11], and a table of elasticities, which capture behavioural responses. The set of equations describe production functions, demand functions, market clearing conditions, income and expenditure functions, and other relationships between the variables of interest.

[11] A SAM is a matrix where columns represent buyers/expenditures and rows represent sellers/receipts. All economic agents (firms, households, government,…) are considered both buyers and sellers.

In the long term, instead, the economic system is flexible. Relative prices change and adjust to reflect the new market situation, where some goods may have become scarcer than in the pre-disaster market. New equipment and skilled labour move in from the outside regions, replacing lost capacities in ways that may differ from the previous situation. The organization of the production system also changes, with new inputs and suppliers substituting for those not available any longer. These substitution flexibilities are incorporated in CGE models. The difficulty is to find data on elasticities for their databases. However, CGE models are the state-of-the-art technique in regional economic modelling and they allow many possibilities for impact and policy analysis (Rose & Liao, 2005). These models are multi-market simulations (which can be disaggregated to study sectorial effects) that are able to represent real-world dynamics such as production and behavioural changes, through input substitutions and relative price changes. Moreover, they can easily model resource constraints, which are likely to be present in a disaster situation. Reviews of the CGE literature can be found in Okuyama (2009) and Hallegatte and Przyluski (2010).

c) Hybrid models

IO models are often considered “too pessimistic”, because they assume that the economic system is incapable of substitution. In reality a firm can, for example, partially reduce losses by substituting usual inputs with others that are not considered suitable for the production process in normal times. Therefore, IO models tend to overestimate the disaster economic impact. On the other hand, CGE models are often considered “too optimistic”, because they assume an economic system that can be more flexible than it is in reality. In a disaster situation, in fact, resources may not be used optimally due to several contingent limitations (e.g. not enough skilled labor is available or can reach the affected area). Therefore, CGE models tend to underestimate impacts.

Both extremes are unlikely in reality and thus several “intermediate” models have also been devised, such as IO models with flexibility (Hallegatte, 2008), or CGE models with reduced substitution elasticity (Rose, Oladosu, & Liao (2007), or other kind of extended or hybrid[12] models. For example, the IO model can be extended by using the Sequential Interindustry Model (SIM) in order to trace the propagation of the impacts through all the production process (Okuyama, Hewings, & Sonis, 2004), or it can be integrated with a GIS model to take into account geographical differences in economic vulnerability (Veen & Logtmeijer, 2005).

Hybrid CGE models, in particular, emphasize the importance of infrastructures such as transportation, water, and electricity networks. Studies of this kind are of fundamental importance, since often these infrastructural services are provided in a linear chain, so that if one link is disrupted, also all the downstream parts are unable to function. Notable examples are the works of Tsuchiya, Tatano, & Okada (2007), Rose and Liao (2005), and Rose *et al.* (2007). The first employs a spatial CGE (SCGE) to analyze the economic impact of transport infrastructure disruptions caused by a hypothetical large earthquake in Japan. The second refines and recalibrates a CGE model in order to study water supply system disruption in Portland, Oregon, also allowing for a decomposition of direct and indirect effects. The third, although not about a natural disaster but a man-made one, provides an analysis of the economic effects of a disruption of the electricity network in Los Angeles, also investigating the role of business resilience.

5. Suggested research directions

This paper has shown that the economics of natural disasters is a flourishing field, but that still has to overcome some challenging issues, starting from being able to actually define what a natural disaster is and to understand how the choice of definitions and threshold criteria can affect the subsequent analysis. However, the main problem that still requires much research attention is how to reduce or treat the large uncertainties on indirect loss estimations, especially in the long-run and possibly including non-monetary costs. This problem is complex and has several roots: data biases, assessment methodologies, limited theoretical insights.

More effort towards a standardization of definitions and terminology will help not only to clarify the different types of disasters and losses, but also to reduce biases and

[12] Often IO and CGE models are hybridized with engineering or geographical models, such as GIS, to better study network and spatial relationships.

increase comparability. This is both true for data collection (databases) and analysis (empirical research). The collection and maintenance of large and detailed datasets is not easy and improving their quality and comparability will require time and effort from several national and international organizations. However, even with biased data there is still much that researchers can do to improve the quality of their analyses. For instance, tackling the problem of data "thinning" (the fact that the further we go back in time, the lower the likelihood that a disaster that had occurred had also been registered in a database). As pointed out by Johansson & Kriström (2015), although such problems are well-known in the statistical literature, the econometric literature still has to take up the challenge to address data quality issues more directly.

Another challenge for the economics of natural disasters research is the problem of better estimating indirect losses, especially non-market ones. As noted in Section 3.3, most impact studies usually rely on output measures, such as GDP, that do not take into account some of the most important "assets" that are damaged, which do not have a clear price, such as public goods or natural capital, or can even be intangible, as human and social capital. Measuring and estimating these costs is, of course, very difficult and therefore only a few studies in the disaster literature have attempted to analyse the environmental and human costs. There are, however, many studies in the valuation, welfare, and natural resources literatures that are devoted to this task (e.g. the already mentioned Thaler & Rosen 1976; Dasgupta & Mäler, 2000; Barbier, 2013). Future research on disaster impact will surely benefit by linking with these other areas of economic research and developing integrated methodologies able to better assess the true costs of a natural disaster.

Finally, the discussion in Section 4.1 has shown that theoretical models to describe the underlying economic dynamics of natural disasters are scarce. Surely, the practical concerns related to the economic recovery in the aftermath of a disaster require empirical methods. However, it is not clear, in the long term, what are the more effective policy actions that can be taken to reduce human and social vulnerability and increase intergenerational welfare. In particular, empirical models have inherent difficulties in separating long-term effects of disasters from those of regular economic activity. A better understanding of these effects can be reached, for example, by developing theoretical models that explain the interactions between business cycles or growth trends and unanticipated large exogenous shocks (see, e.g., Barro, 2009). More generally, theoretical models able to describe intertemporal socioeconomic dynamics under uncertainty, especially in a welfare perspective, will be very useful for devising optimal prevention, mitigation, and adaptation strategies.

6. Conclusion

To summarize, this paper presents an overview of the current status of research in economics of natural disasters. Firstly, it discusses the importance of having standard definitions, the problems of available datasets, and the difficulty of assessing the actual cost of a disaster. Then, it presents the main methods for estimating the impact and effects of natural disasters on the economy. Finally, it proposes some future research directions.

Recently, international interest in this area of research has been shown by the endorsement, by the United Nations General Assembly, of the Sendai Framework for Disaster Risk Reduction (http://www.unisdr.org/we/coordinate/sendai-framework) in 2015. This framework encourages shifting the focus from post-disaster relief to preparedness and prevention policies and calls from more cooperation between the public administration, the private sector, and different research centres. The author of this paper believes that, in order to reduce vulnerability, more and better theory is needed, especially regarding how to evaluate the social and environmental costs of natural disasters. Economic models that also include insights from other research areas and more cooperation between researchers from different disciplines will surely prove very helpful in devising optimal strategies for disaster mitigation and adaptation.

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