# The Economics of Volcanoes*

Johanna Choumert[†], Anaïs Lamour[‡] and Pascale Phélinas[§]

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## Work in progress

**Abstract**

Volcanic activity has always had an effect on populations, yet the economic literature on its short and long-term consequences on household behaviour and economic development is still in its infancy. In this article, we present the state of the literature and raise knowledge gaps, as well as methodological challenges inherent to the economic analysis of volcanic hazards and disasters. We, firstly, present the physical aspects of volcanic activity, and describe available physical data. We then examine what costs should be associated with an eruption and how to assess them. We also discuss the suspected transmission channels at stake at the micro and macro levels and review the few existing evidence on whether and how volcanoes affect welfare and development outcomes. Finally, we discuss key research questions economists should investigate, and identify relevant methodological and data challenges. By highlighting research gaps in the "Economics of volcanoes", we provide future avenues of research that will address policy-relevant debates in the context of greater focus on risk mitigation, adaptation and resilience policies in facing natural disasters.

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[†]Economic Development Initiatives (EDI) Limited, High Wycombe, United Kingdom. email: j.choumert.nkolo@surveybe.com

[‡]LMV and CERDI, IRD/University of Clermont Auvergne, Clermont-Ferrand, France. email: anais.lamour@uca.fr

[§]IRD-CESSMA and CERDI, University of Clermont Auvergne, Clermont-Ferrand, France. email: pascale.phelinas@ird.fr

# 1 Introduction

Volcanic hazard pose a potential threat to almost 500 million people worldwide representing 9% of the world's population (Small and Naumann, 2001). Moreover, according to Ewert and Harpel (2004), the population exposed to volcanic hazards is expected to keep increasing: sustained population growth, migration to areas in close proximity to volcanoes (both urban and rural), but also the possibility of larger eruptions are the main drivers of this trend. Unfortunately, the rise in potential exposure will occur mainly in low and middle-income economies where the population has limited resources but where most of active volcanoes are located. The so-called "Ring of Fire" circles the Pacific Ocean along the Pacific coast of America and Southeast Asia; the Great Rift Valley is a 6,000-mile crack stretching from Lebanon to Mozambique that is still in progress. As a result, many large cities in low and middle-income countries are at threat of a volcanic eruption, such as Mexico City, Manila, Guatemala City, San Salavador, Managua and Quito.

Eruptions can be highly destructive. Volcanic events have killed around 98,000 people and affected about 5.6 million people during the 20th Century (Witham and Oppenheimer, 2005), the common consequences of volcanic hazards including respiratory illness, serious economic losses, destruction or damage to housing, infrastructure and land (Witham and Oppenheimer, 2005). Compared to the excess mortality triggered by other disasters, volcanic fatality counts appear marginal. However rare volcanic catastrophes such as the 2018 eruptions of the Volcan de Fuego, Guatemala, and of the Anak Krakatau volcano, Indonesia, are forceful reminders of the threat of volcanic activity, whereas more moderate but repeated volcanic hazards keep affecting local populations, with around twenty volcanoes with ongoing eruptions at any time around the world.

Despite this risk proving economically significant, the economic analysis of volcanic hazards and disasters is still in its infancy. The economic literature on volcanoes is scant, with very few contributions compared to other physical and social sciences. It is therefore essential to position "volcanoes" in Economics. Essentially, from an economics perspective, volcanoes can be approached through two concepts. The first one is the one of "natural disaster" with both localized and global impacts[1]. The second one is "amenity" (e.g. touristic activity) but this aspect goes beyond the scope of this paper (see Kelman and Mather (2008) and Hearne and Salinas (2002)).

"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" (Hallegatte and Przyluski, 2010). As such, volcanic disasters impose both direct losses and indirect losses. Direct losses include direct market losses and direct non-market losses: on the one hand, the value of direct market

[1] See for instance the 2010 Eyjafjallajökull explosive eruption with global impacts on air traffic (Sigmundsson et al., 2010).

losses can be estimated using market prices for repairing or replacement; on the other hand, it is harder to estimate the value of non-market losses such as impacts of volcanic disasters on morbidity and mortality and impacts on ecosystems and historical assets (although indirect methods are available for some items). Indirect losses are provoked by the consequences of the disaster (such as output losses caused for instance by damages of water, electricity or road infrastructure). These losses can be market and non-market losses.

Furthermore, microeconomic and macroeconomic literature gives many insights into how volcanoes can affect the welfare of the populations living under their threat and the performance of economies, pointing at channels of influence in manifold dimensions and not only at the local scale. As a risk of natural disaster, the risk of an eruption threats all factors of production (labour and physical capital including infrastructure, financial capital and natural resources) and local markets, in an unfair and covariant way. Consequently, volcanic risks are theoretically hard to insure and reinsure for low frequency massive eruptions (view, 2005), still the actual coverage of insurance against more likely and less destructive volcanic hazard such as volcanic ashes is not higher (Adamov and S, 2017). Whereas public interventions toward volcanic risk can be summarized in improved warnings, preparedness programs and emergency plans, there is an acute need for relevant public interventions, such that taking a rigorous quantitative approach to better understand the economic impacts and policy choices - mixing data and methods from geosciences, social and statistical sciences - is a critical first move that economists should make.

In this article, we raise knowledge gaps and methodological challenges in this under-explored topic. Mobilizing the literature in the economics of disasters, environmental and natural resource economics, economics of risk and uncertainty, experimental economics and development economics, we review the concepts and the few research articles focusing on whether and how economies are affected by volcanic activity. We conclude that there are not only many costs to assess that require the methods developed by economists in order to get the full picture of the distributions of volcanic losses, but also a variety of suspected effects and mechanisms to investigate in Microeconomics and Macroeconomics. In particular, the fact that most volcanic losses are localized around volcanoes and that this risk is made tangible in the landscape by easily recognizable and imposing landforms makes it likely that volcanic risk contributes to the creation of poverty traps at the foot of volcanoes. By highlighting research gaps in the "Economics of volcanoes", we provide future avenues of research that will address policy-relevant debates in the context of greater focus on risk mitigation, adaptation and resilience policies in facing natural disasters.

In that sense, this article does not only come within the profuse strands of literature reviews on natural disasters (Hallegatte and Przyluski, 2010; Cavallo, Noy et al., 2011; Sawada and Takasaki, 2017), it also follows up on an issue raised by many empirical studies. Facing data challenges relative to both the low frequency of large disasters and the lack of data on smaller adverse natural events, empiricists in search for variability in their data have to choose between i) cross-country panel settings in which they can have sufficient enough prevalence of one type of natural disaster, but many core institutional and geographic features may be correlated with it (Hsiang and Jina, 2014; Kocornik-Mina et al., 2015), ii) the same settings but within a single country and with fewer chance to be able to disaggregate the effect of one type of natural disaster especially if the country is small and the event is rare (Anttila-Hughes and Hsiang, 2013; Boustan et al., 2018), and iii) case studies of a specific major disaster (Hornbeck, 2012; Deryugina, Kawano, and Levitt, 2018). By discussing concepts of economic analysis in the case of volcanic risk, our work highlights that the varying characteristics of each type of disaster may lead to specific effects that should make one as reluctant to aggregate all disasters into a unique variable in an empirical model, as worried about missing variables.

The rest of the article is organized as follows. Firstly, section 2 presents the physical aspects of volcanic activity, and describe available physical data. Section 3 then examines what costs should be associated with an eruption and how to assess them. We discuss the suspected transmission channels at stake at the micro and macro levels respectively in Section 4 and Section 5 and also review the few existing evidence on whether and how volcanoes affect welfare and development outcomes. Section 6 discusses key research questions economists should investigate, and identify relevant methodological and data challenges. Section 7 concludes.

## 2 Volcanic hazards, volcanic risks and volcanic disasters

According to the UN glossary (United Nations. Secretary General, 2016)[2], a "hazard is a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage". Many hazardous processes have a geological origin including earthquakes, volcanic eruptions, tsunamis, landslides, and are part of the Earth history. Compared to hazard, the concept of risk introduces the idea of probability: "risk is the probability of occurrence of the under examination event and all the possible drawbacks that this event may have" (United Nations. Secretary General, 2016). For a hazard to turn into a disaster, human beings and societies must be largely and adversely affected: 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 resource" (United Nations. Secretary General, 2016).

In short, natural hazards may not lead to risk if the area directly impacted is inhabited, whereas they may turn into disasters if the area impacted is densely populated. Hence, the

[2]See Hallegatte and Przyluski (2010) for a comprehensive discussion around these concepts, debates around their definition and operational challenges with their effective use.

economic implications of a natural event such as an eruption or a landslide will depends on both the characteristics of the physical hazard and the population and assets that are exposed to it.

## 2.1 Characteristics of volcanic activity

The planet's eruptive volcanoes are recorded in the database of the Smithsonian Institution's Global Volcanism Program (2013). This database lists 443 active volcanoes in the world since the beginning of the 20th century that have given rise to 3445 observed eruptions. When information is available, the precise dates (day/month/year) of the beginning and end of the eruption are also indicated. These figures indicate that eruptions occur all year round and almost permanently over various regions of the globe.

There is a great heterogeneity in what is called a volcanic eruption in terms of physical characteristics, intensity, length as well as damages resulting from this type of event. The primary hazards associated with volcanoes fall within two main categories: effusive eruptions release lava or mud flows (lahars) that follow topographic depressions; explosive eruptions project gases and ash that disperses in the atmosphere under the effect of the wind and solid rock fragments (tephra). The last ones are the most dangerous in the sense that they occur with little advance warning and cause the most deaths because populations threatened by gas and burning ash do not have time to evacuate. They also usually affect larger areas because these kind of eruptions throw ashes sometimes up to several kilometres around the volcano. Unfortunately, they are also the most frequent and, according to Small and Naumann (2001), most people exposed to volcanic risk are exposed to explosive rather than effusive eruptions. Within these two main categories, each eruption has its own characteristics and may thus have various physical effects: some of the lava produced is very fluid and flows quickly, while others, more viscous, move slowly. The thickness of tephra ejected varies from incandescent bombs, which can reach a size of several meters, to fine ashes of a size in the order of a millimetre. They also vary in intensity and temporal (length) scales. The magnitude of volcanic eruptions is usually measured using the volcanic explosivity index (VEI) introduced by Newhall and Self (1982). This index indicates the amount of mass ejected during an eruption and the size of the eruption column. It ranges from zero (gentle eruption) to eight (mega-colossal eruption)[3]. As far as duration is concerned, the Smithsonian Institution's Global Volcanism Program reports eruptions lasting from a few days to several years.

In addition, eruptions may trigger by-disasters. According to Gill and Malamud (2014), volcanic eruptions are the natural risk that generates the most secondary risks such as landslides, ground collapse, or wildfire. Volcanic eruptions also occur in earthquake-prone areas because both phenomena, which are unrelated, has the same geological origin. This means

[3] This index indicates eruptions rated at VEI 1 produce between 0.0001 and 0.001 cubic kilometres of tephra ejected. Then, each step in the scale represents an explosivity increase of 10 times.

that populations threatened by a volcanic risk are also threatened by other natural hazards. Last but not least, volcanoes are often close to each other. As a result, some populations may be affected by several volcanoes.

The impact of any eruption also depends on weather (wind, rain) parameters. For instance, the same amount of ash fall associated with the same VEI will have a different impact on populations depending on the wind direction, the amount of precipitation that falls just after the event. Rain may have a leaching effect. Conversely, rain may exacerbate the impact of ash falls as it contributes to compacting. Although areas close to volcanoes support the most productive soils (Kelman and Mather, 2008), the short term impact of ash falls depends on the quantity: slight fallout of ash may fertilize the soil, too much falls contributes to sterilize it.

Even with the current technology, and despite the high level of surveillance of many volcanoes, the probability associated with each of the possible events for each location in the world is far from being certain.Simkin and Siebert (1984) emphasized that, during the last 10 000 years (holocÃ¨ne) 17 of the 21 largest historical eruptions have occurred at volcanoes that had experienced no previous historical eruptions. Among the 176 volcanoes listed by Witham and Oppenheimer (2005), only fifty percent of them erupted once during the 20th Century. However, the volcanoes that erupt least frequently tend to erupt most explosively and produce more fatalities Simkin and Siebert (1994); Simkin (1993).

## 2.2 Measuring the risk of volcanic activity

Volcanic risk assessment, as far as science knows, is not that simple. It is not enough to look at the simple correlation between the presence of a volcano and eruptive events. The heterogeneity of volcanic events, the diversity of socioeconomic outcomes they cause which, in turn, depends on numerous factors, imply that the selection of indicators for volcanic activity is critical in empirical research.

Volcanic events are the best exogenous measure of risk that is captured through three indicators: the number of events or incidents over a given period, the magnitude of volcanic eruptions or the length of an eruption. All these indicators do not depend on countries' level of development. However, these indicators have the disadvantage of being poorly correlated with the potential human and economic impact of the event and give a misleading indication of the potential risk for populations leaving near a volcano. For instance, if a volcanic event occurs in a remote or sparsely populated area, the impact on both human life and capital destruction will be very limited. In contrast, if the event occurs near a big city, the damage will be substantial. This highlights how much the heterogeneity of volcanic events translates into a diversity of adverse impacts with which it is difficult to associate any probability.

The volcanic risk cannot thus be easily measured per se because the potential impact of volcanic events depends on both the volcanic event characteristics' and the population or assets at risk. As a result, it is usually measured through the intensity of its effect, which has unfortunately an endogenous component.

Different databases recording the intensity of the impact of volcanic activity exists (Tanguy et al., 1998; Simkin, Siebert, and Blong, 2001; Witham and Oppenheimer, 2005; Guha-Sapir, Below, and Hoyois, 2019; UNDRR). Among these sources, the emergency Events Database (EM-DAT) is the only database in open access, which provides the intensity of the impact of natural disasters worldwide and includes human as well as economic impacts [4]. Three main outcomes of the intensity of a shock are recorded: the number of people killed, the number of people affected and the damage estimated in US dollars. Because the data entry procedure is subject to many checks, this database is widely used by different international research institutions for validating hazard risk models (e.g. United Nations Environment Program and Joint Research Center of the European Union), for measuring achievement of different disaster risk reduction programs worldwide (e.g. the Global Assessment Report of UNISDR), and in academic research on natural disasters.

However, as far as volcanic events are concerned, many researchers have pointed out a number of deficiencies and measurement errors. First, only disaster events are recorded. To be included in EM-DAT, disasters must have killed ten or more persons, or affected one hundred or more people, or a state of emergency have to be declared, or call for international assistance. This definition means that small events are missing. Unfortunately, many volcanic events occur at a limited geographical scale and will not be recorded as "disasters". However, repeated small or medium events such as ash falls may have long-term health impacts and significant economic consequences (Choumert-Nkolo and Phélinas, 2019). Second, different historical records of casualties driven by volcanic events show considerable uncertainties in the number of victims (Tanguy et al., 1998; Simkin, Siebert, and Blong, 2001; Witham and Oppenheimer, 2005). There are two main reasons behind these discrepancies. Records in the number of fatalities are often based on vague qualitative indications or approximations and not on accurate "confirmed" counts (Simkin, Siebert, and Blong, 2001; Witham and Oppenheimer, 2005). Some effects of the shock may appear in the long run. For instance, some people may die well after the eruption's first month from respiratory illness, injuries caused by the event, by indirect food shortage or malnutrition, or by poor housing and sanitary conditions in evacuation areas (Hansell, Horwell, and Oppenheimer, 2006; Halkos and Zisiadou, 2018). Although records for recent events are more accurate, the poor reliability of historical data raises the problem of time series consistency. Any rise may be a statistical artefact resulting from a better reporting or it may be the result of more severe exposition or increase in population densities. Note that the final fatality figures in EM-DAT may be updated even long after the disaster has occurred.

Third, according to Witham and Oppenheimer (2005), the term "affected" is problematic and confusing because people are affected in very different ways. In addition, its content

[4] For an exhaustive comparison of Desinventar and EM-DAT, see De Groeve, Poljansek, and Ehrlich (2013).

seems to have changed over time. It initially referred primarily to evacuees and homeless. Later on, it included persons under alert and people seriously affected by ash falls. However, there are no standards for collecting all these aspects. In particular, people moderately affected by ash fall are usually unreported. However, ash falls, even moderate, can seriously affect both domestic and daily productive activities. For instance, some people may not restart their former economic activities because their capital (land and livestock) has been destroyed or seriously damaged. Hence, the figures for impacted persons are at best rough approximations. It is the most likely figure to have large measurement error.

Fourth, the accuracy of the numbers of killed/injured/affected/missing persons depends on the level of development of the country as well as the location of the event. Persons living in remote areas and in developing economies have a lower probability to be reported in the statistics. In addition, the real cause of death/injury might be unclear because health services and doctors able to make a reliable diagnosis are lacking. The amount of economic loss also depends on the country's economic level measured by its GDP per capita. The magnitude of economic losses is expected to be greater in richer countries because there is more private property and assets at risk, and public infrastructure is more developed. Furthermore, in developing economies estimating economic damage is not easy because markets are sometimes missing for some factors, goods and services, especially in rural areas, and a price cannot be easily observed. For instance, crop or livestock losses are difficult to quantify.

Fifth, routine data collection rests with national policies and administration. The numbers reported are highly sensitive figures and could be tainted with errors reflecting socio-political considerations, or the willingness to secure a higher volume of international aid. All the issues raised above point to the risk that the probability that an event will be recorded is arguably endogenous to the country level of income, and thus damage. The poor data quality limits volcanic risks assessment by scientists as well as policy makers and is an obstacle to understanding response, adaptation, and resilience to the exposure of a volcanic hazard. Promoting improvements in data should remain a key priority for all stakeholders.

## 3 What are the costs of volcanic disasters?

Thereâs a large interest in measuring the economic costs of natural disasters among academia, insurance companies and public authorities in charge of post-disasters recovery and risk management. Yet, not much is known on the costs of volcanic events although there exists a large spectrum of methodological and approaches to assess these costs. In this section, we thus examine the economic costs of volcanic events, by firstly providing a review of state-of-the art concepts and methodologies for measuring the costs of natural disasters, as presented by Hallegatte and Przyluski (2010), secondly, by examining existing cost estimates and finally by giving suggestions for future research.

## 3.1 Valuation concepts

Volcanic events generate significant natural, social, human and built capital losses. This section thus provides an overview of commonly used concepts in costs assessments of natural disasters. The conceptual framework is no different from the one related to natural disasters as a whole (see Hallegatte and Przyluski (2010) for a thorough overview of the literature).

Direct losses are immediate consequences of the physical volcanic disaster. They are composed of market and non-market losses. One the one hand, prices can be observed for market losses and typically include damage or destruction of assets, which value can be imputed through reparation or replacement costs. Yet, estimating the monetary value of these losses is far from straightforward and existing methods do not account for distributional impacts of such capital losses (Gaddis et al., 2007). In addition, since these methods are based on market prices, they are subject to a series of constraints which are context specific. These are the existence of informal housing or missing market.

Loss of build capital and human capital are major components of these direct costs. These notably include buildings, dwellings, schools, crops, livestock, energy infrastructure, telecommunications, road infrastructure, water systems, etc. On the other hand, prices canât easily be observed for non-market losses, which can include damage or destruction of cultural and historical sites, of ecosystems, or health impacts. The economics literature provides a wide range of tools to estimate the economic value of non-market goods and services, yet there persist many debates (see non-market valuation techniques (Champ et al., 2003); statistical value of human life (Doucouliagos, Stanley, and Giles, 2012)) with respect to the terminologies and tools used. Indirect losses arise in the aftermath of the volcanic physical disaster. There is no consensus on the typology of these indirect losses. As a consequence, Hallegatte and Przyluski (2010) suggest the use of the following criteria: "First, indirect losses are caused by secondary effects, not by the hazard itself. Indirect costs can be caused by hazard destructions or by business interruptions. In addition to this obvious criterion, costs are indirect if they are spanning on a longer period of time, a larger spatial scale or in a different economic sector than the disaster itselfâ. They subsequently add that âwith this definition, the reduction in agriculture yield, and in farmer income, are considered as direct costs, consistent with intuition, while the impacts on other economic sector trading with the agricultural sector are indirect costs." Such indirect losses can take both the form or market and non-market losses. These include for instance loss of earnings or employment following road damage or decrease in consumer demand, as well as short term and run impacts on macroeconomic aggregates, such as poverty rates, GDP or government expenditure (these macroeconomic effects can also be referred as secondary effects (Martí and Ernst, 2009)). See further discussions on these macroeconomic costs in Section 5.

Indirect costs are a major component of total cost (Hallegatte and Przyluski, 2010; Martí and Ernst, 2009) but most calculated costs are direct costs, which thus leads to an underestimation of the costs of disasters. As a matter of fact, costs reported in the aftermath of a disaster would typically refer to more tangible costs, whereas other intangible costs could be reported in non-monetary terms (e.g. the number of affected persons).

### 3.2 Future research and methodological challenges

There remain significant research and knowledge gap on the total economic costs of volcanic events. To date, there is no clear estimate of the total economic costs of volcanic events, despite the fact they affect millions. These costs are spread out at different magnitudes and at temporal and spatial scales.

As with any other type of natural disaster, an obvious consequence of volcanic eruptions is the excess mortality and morbidity they can directly cause. To our knowledge, there is no research to date on the valuation of exposure to volcanic activity in terms of health-related costs for residents or poor labor market outcomes in supply and/or productivity â effects that has been evidenced in the case of air pollution from anthropogenic sources (Graff Zivin and Neidell, 2012; Deryugina et al., Forthcoming).

Since these costs go beyond physical destruction costs, economics allows us the quantification of welfare variation resulting from volcanic events. Cost assessment of volcanic events is a challenging exercise both from a methodological point of view and operational one. In addition, cost assessment exercises say little about the adaptive behaviour of affected households and about their response to such shocks. In order to better inform risk management and post-disaster policies, economists should thus put more efforts in understanding household behaviour in the presence of volcanic risk and in the aftermath of a disaster.

## 4 Microeconomics of volcanoes

Valuating the trends and costs of volcanic events is crucial to determine whether a public intervention aiming at mitigating them is cost-efficient, however these numbers fail to detail how volcanoes affect individuals' well-being. Aggregate losses appearing as negligible may indicate disastrous socioeconomic impacts when inflicted to households who owned very little and where infrastructure and equipment were insubstantial at first.

### 4.1 Households' responses

The analysis of the welfare losses inflicted on exposed households by a natural disaster risk uses concepts developed by two arrays of microeconomic studies, the first one focusing on ex-post impacts, when a shock occurs, and the second one considering ex-ante strategies used by households to manage a risk, in anticipation of a future shock. In addition, due to the characteristics of volcanic risk and their localization in low-income regions, both ex-post and ex-ante effects in this case can be seen in the light of the linkages between this risk, the poverty status of exposed individuals and local market inefficiencies. On the one hand, household assets strongly define whether the household will be able to avoid well-being losses when a disaster strikes (high vulnerability) and to recover from them (low resilience). For a vulnerable household, the occurrence of a natural disaster can thus increase the probability that it becomes unable to meet basic needs and caught in a poverty trap, provoking dramatic adverse effect on its welfare. Poverty appears as both a driver and a consequence of disaster-induced losses. On the other hand, the threat itself of a disaster cannot be efficiently transferred away (missing or incomplete insurance market) from exposed households and small entrepreneurs, affecting their welfare and investment given risk aversion and in spite of sophisticated but costly ex-ante self-insurance arrangements. The responses of individuals to risk thus perpetuate poverty.

The literature on coping strategies that individuals use to manage a risky context for production and consumption decisions has documented many pieces of evidence showing that these strategies lower incomes and investment at the household level (Rosenzweig and Binswanger, 1993; Elbers, Gunning, and Kinsey, 2007). For the poorest who have no access to financial markets and sacrifice allocative efficiency in order to smooth income fluctuations over time, these strategies can result in the introduction of productive activities with low marginal returns into more diversified portfolios (Rosenzweig and Binswanger, 1993), increasing the share of their capital dedicated to subsistence farming (Fafchamps, 1992) or to off-farm activities (Fafchamps, 1993; Macours, 2013) as well as a de-capitalization of productive assets (Rosenzweig and Wolpin, 1993). Yet the self-insurance feature of these strategies identified in cases of weather variability may only stand if capital stocks of farms and of off-farm businesses as well as precautionary savings in the form of grains, livestock and other highly liquid assets are immune to the shock, a condition that is hardly expected when a volcanic eruption strikes.

As with asset sales, informal insurance mechanism consisting in sharing risks with a network of friends and relatives may be seriously challenged around volcanoes, because mutual assistance links are traditionally based on geographical proximity (Udry, 1994; Fafchamps and Gubert, 2007) while a volcanic event has a covariant nature. Diversifying the kinship network by sending a household member to work away from an exposed area is a well documented strategy used to receive remittances in case of a shock (Stark and Lucas, 1988; Rosenzweig and Stark, 1989) including natural disasters (Gröger and Zylberberg, 2016). However, keep living together provides family members with multiple benefits that are more costly to generate once a family is split up (Fafchamps and Quisumbing, 2007). Geographical distance can also be seen as a physical barrier in case of an eruption due to damaged infrastructure that can limit further the influx of support from outside the affected area. Mobile technology may facilitate longer-distance inter-household assistance (Jack and Suri, 2014), however those with the greatest need may not benefit from it since mobile phone-based transfers require owning mobile phones and some empirical evidence suggests that poorer mobile owners are less likely to receive these transfers in the aftermath of a natural disaster (Blumenstock, Eagle, and Fafchamps, 2016).

Therefore household responses to a volcanic risk are likely to at best succeed in partial insurance, leading one to expect a decline in consumption, health and education expenses when the uninsured eruption occurs, with adverse and persistent impact on well-being (Dercon, 2004) that may be transmitted to next generations and affect girls more than boys (Maccini and Yang, 2009). Due to the characteristics of that risk â covariant and geographically defined, while triggering ex ante coping strategies but damaging capital stocks when a shock occurs â the magnitude of overall volcano-induced losses is expected to be large (Ligon and Schechter, 2003; Elbers, Gunning, and Kinsey, 2007) and unevenly distributed.

Population declines through outmigration from an area where a disaster has destroyed part of the capital stocks, infrastructure and natural resources has been proven to be a predominant adjustment to re-establish labor market equilibrium (Hornbeck, 2012). Yet an eruption may not only incite residents to leave affected areas through the loss of income-generating opportunities at the local level, it may also counteract outmigration. First and despite the ensued destructions that can shrink the local housing market supply, relative land prices are likely to increase in close safer areas in the medium run after an eruption, pricing out of these safer areas poor households who are encouraged instead to stay in affected areas or to move in (Boustan et al., 2018). Secondly, disasters make more costly the access to financing to source the substantial up-front costs that migration requires, resulting in credit constraints more likely to bind (Yang, 2008) Ṫherefore, migration flows following volcanic eruptions may worsen inequality as the rich move away from affected areas while the poor are left behind.

In such a setting where households keep bearing the risk of uninsured losses of livelihoods, research has also identified demand-side causes for the socially inefficient levels of self-protection when available (both insurance arrangements and risk-reducing measures). The rapid expansion of many cities located at the foot of volcanoes has led people to settle informally further up the flanks of volcanoes and on lahar-prone valleys, whereas insecure land tenure disincentives building improvements with resistant material and design since another may have grabbed the land by the time an eruption strikes (Do and Iyer, 2008). Concomitantly, pressures for urban land encourage upstream landowners to divert marginal, draining and rough terrains from their mitigation properties by flattening them for construction, generating negative externalities downwards in case of an eruption. In addition, public relief programs and private charity are a well-known zero-premium substitute for self-protection efforts that can be reasonably anticipated by households threaten by volcanic eruptions (Coate, 1995). Called charity hazard (Browne and Hoyt, 2000), this crowding out effect on self-protection with exposed people relying upon ex-post aid is all the more of an issue since on the one hand it can affect the supply-side of the insurance market and drive a vicious circle of higher premiums and lower take-up, and on the other hand, assistance expectations can be endogenously dependent on the pre-disaster level of self-protection in the neighbourhood (Arvan and Nickerson, 2006; Grislain-Letrémy, 2018). Besides the certainty about receiving assistance in case of a shock is a condition for a strong crowding-out effect (Raschky et al., 2013). It may be a widespread belief among populations under a volcano, fuelled by the extensive media coverage they can expect from an event as sensational as an erupting volcano.

All of these insights about how volcanic risk can contribute to allocative inefficiency and inequity share the assumption that exposed individuals found their decisions on an accurate knowledge of losses and probabilities, as well as on clear and stable preferences over various risks and throughout their lives. However, the low frequency inherent to a volcanic risk induces that past experience and collective memory rarely provide a good prediction of the probability distribution of hazard types, intensities and associated losses. Limited preparedness through information and education campaigns, coupled with emergency alarm systems failing at the institutional (coordination) and technical levels, are additional informational barriers explaining why early responses can be far from optimal once the imminence and severity of a volcanic event are known. They have been widely implicated in explaining how the predicted and moderate 1985 el Nevado del Ruiz eruption has become the second deadliest volcanic disaster of this century (D'Ercole, 1989), and are of special concern in these eruption cases where a by-disaster can strike unannounced if a primary hazard has damaged electric power systems and telecommunication networks.

## 4.2 Review of micro studies on volcanic risk

Whereas the microeconomic literature raises concerns about a risk such as the volcanic one being an issue for economic development, there is only little evidence of its effects on households such that there is no evidence-based guidelines to support the design of efficient public interventions.

On physical capital accumulation, Stephane (2018) measured that an Indonesian farm at risk of an eruption would have equipped itself with 33% to 51% less productive assets after fifty years as compared with a similar farm outside the threaten area. His result is based on a stochastic growth model calibrated with panel data from the Indonesian Family Life survey. He simulated capital stocks over time resulting from the investment decision affected by the risk of damages in the absence of a shock and by the change in risk perception ensued from past eruptions, jointly with the damages in case of an eruption. This allowed him to decompose the overall effect of volcanic risk and found that only half of it is due to damages from actual eruptions, while the ex-ante effect yet accounts for a capital stock differential of -7% to -17% between an affected and a non-affected farm.

Consistent with this result on depressed investment in volcanic areas and also in Indonesia, Faurie et al. (2016) showed that a sample of individuals more exposed to volcanic risk from Mount Merapi on Java are less willing to invest in a risky option as compared with individuals in a less affected area of the island. Using a behavioral experiment consisting in a portfolio choice task and collecting participants' DNA samples to classify them according to their variants of a gene associated with novelty seeking, the authors detected that these variants are not evenly distributed between the higher-risk and the lower-risk areas whereas both sites are geographically close. They rather provided evidence that this genetic disparity is a stronger determinant of the behavioral differences observed in the experiment as compared with the place of residence, and further concluded that genetic differentiation have occurred as an adaptation to the volcanic risk, favouring risk-averse attitudes among the most exposed inhabitants.

The latter findings seem in conflict with one of the channels through which environmental risk can spur migration. Facing the unfair prospect of welfare losses, the more risk averse an inhabitant of a volcanic area is, the more prone to opt for outmigration he/she should be. The manifold barriers counteracting migration are likely to be involved in the case studied by Faurie et al. (2016), the average reported distance between birthplace and place of residence being less than two kilometers among both areas. Nevertheless, when cumulated with these barriers, an often-mentioned assumption may also compensate individuals for bearing a volcanic risk, even risk averse people. It relates to land, a strategic capital asset for farming households, and states that improved soil quality derived from nutrients that ash falls bring and cooler temperatures associated with higher altitudes and concomitant with slower bacterial action, convey a gain in utility explaining human settlements in volcanic areas, in particular why Java is one of the most population-dense places on earth. Studying the cases of local communities living at risk of Dieng caldera and Mount Merapi on Java, Lavigne et al. (2008) argued that potato farmers and sand miners tolerate the risk in spite of frequent deaths and asset destructions from volcanic hazards because these activities generate much more incomes than other occupations. As an illustration, the authors reported that potato fields have been extended to a well-known designated danger zone threaten by lethal volcanic hazards, in response to a rising demand for such vegetables.

Empirically testing in Ecuador the assumption that volcanic farmlands convey net benefits per se to their owners due to their high productivity and despite the risk of crops and livestock being damaged by an eruption, Choumert-Nkolo and Phélinas (2019) revealed that farmlands at risk of ash falls from the Tungurahua volcano are rather depreciated by a negative premium of 21%. Their result is based on a hedonic model applied to primary micro data from an area with volcanic ash deposits and another one selected because it had no eruptive deposit but shares many geographical similarities with the affected site â including its altitude. As such, if their finding does not exclude that altitude-related factors may provide an economic benefit when living on volcanic lands, it signals that the fertilizing effect of volcano-specific ashes does not countervail at all the adverse impact of volcanic risk on the welfare of the agricultural household who owns the land. The discount on volcanic farmlands rather tends to support that households living on the flanks of volcanoes may be unable to afford to buy land in a safer area, at least in the medium run.

Choumert-Nkolo and Phélinas (2019) also provided evidence on non-agricultural labor markets that shows a lower participation rate in the area under the threat of the Tungurahua volcano, whereas the shares of farm workers are comparable between sites. In order to explain why households do not engage to a greater extent in diversifying their economic activities as a response to the volcanic risk, the authors make two arguments. First, educational attainment is lower among workers in the risky area, making them more likely to lack the skills required by off-farm jobs. Secondly, job opportunities also seem sparser than in the comparison area.

Consistent with both arguments and further demonstrating that these circumstances can result from past eruptions, Caruso (2017) showed that volcanic eruptions occurred in Latin America during the twentieth century have engendered long-lasting negative effects on the education and employment of affected individuals and of their children too. Using micro data from national censuses and both EM-DAT and DesInventar databases in order to identify individuals affected as children by a volcanic hazard as well as their age when it happened, the author estimated that above-the-median-intensity events generated a loss of years of schooling corresponding to a period from 3 weeks to more than 4 months among individuals affected in their childhood or in utero. This negative effect on education can also be observed when considering smaller volcanic hazards, especially for individuals exposed during the in utero period. The author also presented evidence that most people affected by an eruption in their childhood or during the in utero period are more likely to be unable to work because of any kind of disability, while a larger increase in the probability of being unemployed in the long term was also detected, but only for the ones who were exposed before school age. Furthermore, some suggestive evidence of the intergenerational transmission was brought, with some children attending school for a shorter period and experiencing more child labor if one of their parents was exposed to an eruption in his/her childhood.

Alteration of parents' abilities to provide nurturing environments to children has been established as a highly relevant mechanism underlying the persistence of a shock suffered in early life or by parents on educational and health outcomes, and was confirmed in an Indonesian case following volcanic eruptions by Schwefer (2018). The latter study consists in an impact evaluation of a recent eruption of Mount Kelud and Mount Merapi based on a difference-in-difference approach using monthly data collected by an NGO across the country. Sampled households were assigned a treated status if the grey literature reviewed by the author mentioned their current community as affected by volcanic hazards during the eruptions. The results suggest that affected households are more likely to suffer from domestic violence by 4% due to the eruptions, jointly with higher alcohol or drug abuse and lower reported emotional well-being. The author also attributed a decrease in average household expenditures to the volcanic shock, using regional data from the World Bank. Furthermore, the eruption impact on the prevalence of domestic violence was found to be much more higher among a subsample of internally displaced people, some of them who had to move due to a previous eruption of Mount Merapi. This finding may result from social networks, and thereby social control and mutual assistance, made weaker by forced displacement, whereas they may have been more effective in limiting the adverse effect of the eruption among other affected communities.

Some evidence presented by Stephane (2018) gives credit to the role of social capital in case of a volcanic event. He estimated the effect of a variable measuring the thickness of volcanic ashes in several Ecuadorian communities around the Tungurahua volcano, on the social capital of their inhabitants using primary data. He founds that the willingness to help others and contribute to collective goods, as well as the size of the informal assistance networks, increase as the volcanic deposits get more prominent. Motivated by theoretical insights, the author however showed that interpersonal cooperation are fostered only in communities with large wealth disparities between their members whereas it tends to decrease with the homogeneity of the communities. Therefore, households from the most homogeneous communities may be more vulnerable and less resilient to all shocks including idiosyncratic ones in the aftermath of an eruption.

Overall, most of the evidence points to the existence of poverty traps on the flanks of volcanoes, with fewer physical and human capital accumulation, as well as less social capital if the community is only composed with poor households. Among all natural disasters, Caruso (2017) found that volcanoes have been producing the most devastating long-term effects on wealth. He further showed that using the location of individuals at the time of the surveys instead of their place of birth considerably escalates the magnitude of the effects he estimated. Some of the children born in a place hit by an eruption have been in fact raised elsewhere, and as such, classifying them as affected may have attenuated the effects found. This argument is in line with the idea that migration serves as a coping strategy against natural disasters. More worrisome is that the children from households which were not living in the place during the eruption but moved in afterwards may have been affected as well in their development, due to a detrimental local context or else because of some specificities of these incoming families. Only inconclusive empirical results can be found in the literature on migration decisions following an eruption. They come from Bohra-Mishra, Oppenheimer, and Hsiang (2014) who estimated the effects of different variables measuring eruption intensity of past events from DesInventar database, on permanent inter-provincial migration over three periods from the Indonesian Family Life Survey. When using the number of fatalities, an eruption was found to reduce the propensity of a household to outmigrate from an affected area to another province, whereas using the number of injured people resulted in estimating the opposite effect, while no effect of the number of houses destroyed was detected.

Following the idea that migration may help households to cope with volcanic risk, one might think that relocating affected populations in the aftermath of an eruption can be an efficient public intervention to escape the aforementioned disastrous consequences. Not to mention previous evidence on disproportionate domestic violence among internally displaced people found by Schwefer (2018), the few other insights from the literature also state that the efficiency of relocation programs in case of an eruption is not straightforward. Choumert-Nkolo and Phélinas (2019) cautioned that farmers settled around volcanoes have skills that may be low transferable to other locations or sectors, due to the specificities of the volcanic soils they manage and thus of their experience-based knowledge, as well as because of their lower educational attainment. Wilson et al. (2011) added that the relative success of a relocation program in Chile after the 1991 eruption of Mount Hudson has only reached to temporary moves with many farmers returning.

Accordingly, mitigation measures through improved alarm systems and post-eruption emergency plans prove crucial. Stephane (2018) however warned about a counterproductive effect of such public efforts on the migration decision of households living at risk of the Tungurahua volcano. Using the same dataset as previously mentioned, he estimated that other things being equal, the more a household head trusts in the national geographical institute and in the public authorities, the greater the proportion of his children who stay in the same parish is. This result is more worrisome in light of one of his previous findings which stated that trust towards these institutions was fostered by the intensity of a past eruption. He argued that highly exposed individuals may reward with more confidence the authorities for the warning and thus the opportunity to act preventively. Overall, mitigation measures may hamper outmigration from affected areas by proving efficient in reducing the expectation of volcano-induced damages.

# 5 Macroeconomics of volcanoes

Are natural disasters such as a volcanic event a tremendous obstacle to economic growth and development in most disaster-prone countries? The issue is far from settled. This section first explores the mechanisms by which natural disasters can affect economic activity. We then examine whether the empirical literature supports the idea that volcanic events have a powerfully negative effect on economic growth.

## 5.1 Identifying transmission channels

From a theoretical point of view, the effect of a disaster on subsequent economic growth is ambiguous. Growth theories suggest either a slowdown in growth in the short and long term arising from the destruction of capital, or an economic boom resulting from the reconstruction effort, or no effect for economies with a greater capacity to absorb shocks.

The traditional neoclassical growth theory teaches us that the immediate loss of the physical capital stock following a natural event shifts the production possibility frontier to the left because the capital per head decreases as well as the productivity of essential assets such as land. Human capital may also disappear with death and international migration of population[5]. Disruptions in the transport of goods and people, deficiencies in infrastructures and communications are also likely to disturb the supply chain management and thus the production of goods and services. As a result, short-term GDP growth should slow down, and, depending on various factors discussed below, the economy could enter a phase of long-term stagnation.

However, this pessimistic scenario may induce governments to implement countercyclical policies. If public expenditure increase as a response to a disaster, the multiplier effect of this expense may cancel out the initial drop in production. An increase in output is even possible, depending on the sign and the magnitude of the multiplier. Conversely, if public spending follows the decline in tax revenues, then the negative effect of the disaster on economic activity could be reinforced. The final response of output depends on the fiscal space available to the government for financing public deficit (Melecky and Raddatz, 2014). External aid and remittances could also lessen the adverse macroeconomic impact if the international community increases the flow of funds to affected countries to help the reconstruction process (Raddatz, 2009).

In contrast, endogenous growth models consider that the destruction of productive capital may lead to a "Schumpeterian creative destruction effect". On one side, the destruction of obsolete and unprofitable technologies would have a "cleansingâ effect on the productive system and provide an opportunity to adopt new technologies. The replacement of old equipment and infrastructure should result in a boom in activity following the event, whereas new capital is expected to be more efficient than the one that was destroyed. On the other side, increased risk of physical capital destruction may lead to an increased human capital investment because the latter becomes more attractive. The fact that the physical capital is rarely insured against natural events, even in countries with well-developed insurance markets, might reinforce the attractiveness of human capital investment, which is less risk-prone to disaster than the physical one. This higher human capital may in turn foster the adoption of new technology. As a result, the growth rate of total factor productivity should increase (Skidmore and Toya, 2002). In addition, disasters may also create new industrial and commercial opportunities (Albala-Bertrand, 1993).

However, renovation could be excessively slow if the economy is credit constrained, factor markets not functioning well, institutions inadequate, and access to international market limited. This destructive creation process may also entail reallocation processes, which could prevent countries to get back to their growth path. The reallocation of factors following a disaster may lead to substantial job losses in the short term. On a longer term, it may

[5] However, the EM-DAT database indicates that the potential for destruction of physical capital largely dominates the destruction of human capital (death).

lead to a permanent shift in the location of economic activities and population if the non-affected areas become more attractive and if capital and populations are highly mobile Ager et al. (2019). The catastrophe can, therefore, initiate a self-enforcing process of agglomeration in non-affected areas, leaving the affected areas far behind. The final impact on growth will also depend on many other key variables. First, the magnitude of the event is important. If the share of capital destroyed is too low compared to the total capital available for production it cannot weaken the growth of output.

Second, the geographic location of the disaster (urban/rural; coastal/inland) matters because it determines whether the event hit a particularly sensitive sector of the economy (agriculture, mining or petroleum activity). The final effect on economic growth depends on the forward and backward linkages between the sector affected and the rest of the economy. The ability of the affected regions to attract transfers from the central government also helps to determine the local impact of the disaster (Noy and Vu, 2010). As a result, disasters affect small countries (especially island) more than large ones because their economies rely on very few sectors, typically two, agriculture and tourism. Hence, they are less able to rebound from the macroeconomic impact of a natural disaster through inter-sectoral or inter regional-transfers (Auffret, 2003; Coffman and Noy, 2012).

Third, the disaster may interfere with ongoing social and political developments or pessimistic or depressive economic expectations. Several contributions have stressed the importance of the institutional framework in the ability of economies to rebound from a natural disaster (Raschky, 2008; Raddatz, 2009; Noy, 2009). Fourth, the macroeconomic effects of natural disasters vary with countries' structural characteristics such as the level of development. Natural disasters are expected to have stronger consequences in developing countries (Fomby, Ikeda, and Loayza, 2009; Toya and Skidmore, 2007; Noy, 2009; Raddatz, 2009). A first reason is the predominance of the agricultural sector in these countries GDP. Yet, agricultural production is highly vulnerable to environmental conditions. In a more diversified productive structure, powerful endogenous compensation mechanisms such as investment expenditure can neutralize the negative sectoral impact of the disaster. A second reason is that these countries may lack human and material capital, organization ability, and financial resources to get back to their growth path (Toya and Skidmore, 2007; Crespo Cuaresma, Hlouskova, and Obersteiner, 2008).

Finally, there is a possibility that the focus on economic growth does not identify properly the channels of transmission of a natural catastrophe (Mohan, Ouattara, and Strobl, 2018; Cunado and Ferreira, 2014). Yet, the components of economic growth may be affected differently by a natural disaster, both in direction and timing. Shorter-term impacts (usually up to three years) are likely to be negative because of a direct loss of output. Imports may start by increasing to meet excess local demand for consumer goods but also intermediate goods related to the reconstruction of equipment. Lagged negative effects on exports are expected because countries are used to store export products. This will translate into a trade deficit increase (Albala-Bertrand, 1993). The overall investment, whether domestic or foreign, private or public, may be boosted by the reconstruction effort and maintenance of damaged infrastructures. Whether public expenditure will increase depends on many factors such as the ability of governments to raise funds and increase deficits, the extent to which public revenue decline due to the contraction of economic activity, access to international financial markets, significance of aid flow relative to the extent of damage, and insurance penetration (Melecky and Raddatz, 2011). Private consumption will decrease unless the loss of assets or income is insured, or if people are drawing from their savings or receive remittances.

In summary, the net impact of a disaster on the economy will depend on the sign and relative contribution of each component underlying economic growth, which, in turn, depends on the country-specific characteristics of the economy.

## 5.2 The empirical literature

Because the dynamics of growth after a natural disaster are complex, the empirical literature provides mixed, even contradicting conclusions about the direction and magnitude of macroeconomic implications of natural disasters. For example, Cunado and Ferreira (2014); Skidmore and Toya (2002); Noy and Vu (2010) find that natural disasters are beneficial and have a positive impact on long-term growth mainly through growth in factor productivity. Leiter, Oberhofer, and Raschky (2009) shows that flooding has a positive impact on the growth of assets and employment of firms located in regions hit by a flood. Other authors find the opposite effect Felbermayr and Gröschl (2014); Hallegatte and Dumas (2009); Hochrainer (2009); Raddatz (2009); Strobl (2012) or insignificant effect Albala-Bertrand (1993); Cavallo et al. (2013) of natural disasters on GDP per capita growth.

Different type of natural disasters do have different effects. Few studies specialize in a specific type of disaster, and, as far as we know, none of the studies focused on volcanic events. Geological disasters are sometimes isolated in the analysis, but in addition to volcanic eruptions, they include earthquakes, landslides, and tidal waves. Since these disasters are of a very different nature, with a different relative threat to property and life, we might expect conflicting effects on an economic decision. Grouping them may thus mask heterogeneous impacts and it is difficult to draw robust conclusions on the impact of volcanic events from the analysis of geological disasters.

The study of Felbermayr and Gröschl (2014), which analyses the impact of different types of natural disasters on growth, shows that volcanic eruptions are the only events that do not reduce economic growth. This result may arise from their database, which includes few events. Another reason is that volcanic events are geographically limited in the region or even the department where the volcano is located and therefore affect a country's economic growth to a lesser extent.

### 5.3 Future research

The overall persistence of the effects of volcanic risk is particularly difficult to comprehend when related to economic growth and human development. Damaging not only local labor supply but also capital stocks, infrastructure, and natural resources, volcanic eruptions entail output losses.

The above literature review suggests that natural disasters have complex effects on the economy. Therefore, much remain to be done in exploring the macroeconomic aftermath of volcanic events. There is in particular a strong need for a more disaggregated analysis of the impact of volcanic events on economic growth, according to the potential mechanisms through which it may affect the different sectors of the economy, and the level of development of the affected countries. Understanding the interactions between the affected area and the national economy is lacking. Looking at volcanic impact on environmental capital (for example land fertility) and its economic repercussions would be another key point. Some other impacts such as school enrolment or the local public revenue and spending, or upward pressure on prices have also been under-investigated.

## 6 Challenge relative to socioeconomic data

From both a microeconomic and macroeconomic analysis perspective, the lack of work about volcanic disasters can be explained by the lack of socio-economic data in affected areas, as well by the spatial scale of exiting data sets.

Indeed, the availability of socio-economic data about populations affected by volcanic hazards lags behind the availability of physical information (See Section 2). Economists thus lack sufficient quantitative household level data to provide rigorous analysis around risk management and adaptation policies to volcanic hazards, even more so that the latter are very localized. On the one hand, the spatial scale of existing household surveys (secondary data) doesnât allow analysing very localized events; on the other hand, implementing a household survey (primary data) in volcanic-affected communities raises a variety of operational and ethical challenges.

With regards to secondary data sources, although there exist various household-level datasets in countries affected by volcanic hazards, they are typically not available in the spatial scale that is needed for localized volcanic hazards. Located on the Pacific Ring of Fire and with 142 volcanoes, Indonesia provides a good illustration of this issue. More than 8.6 million inhabitants live at 10 km from a volcano, more than 68 m at 30 km and more than 179 m at 100 km (Brown et al., 2015) over a population of 263 m. Yet, existing large-scale datasets hardly cover these populations. Using four waves of the Indonesian Family Life Survey (IFLS) from 1993-2007, Stephane (2018) calculated the distances between sampled communities and volcanoes and found that they were too far (generally at more than 20 km). Besides, even if a survey covers clusters close to volcanoes, by construction a cluster would contain information for around 8 to 20 households limiting the potential for rigorous quantitative analysis. Overall, despite the existence of more longitudinal surveys in many countries, sample sizes are not sufficient to analyse very localized phenomena like volcanic hazards.

One way to downscale socio-economic data is to directly collect primary data in the affected zones. However, this raises a series of ethical questions as to how to collect data in disaster-affected areas. Indeed, existing research highlights that volcanic hazards have severe impacts on the psychological health of affected populations (Paton, Millar, and Johnston, 2001; Ruiz and Hernández, 2014). When conducting a field survey in post-disasters areas, it is thus recommended that researchers and field teams consider these populations as vulnerable ones as suggested by de Jong, K.C., and Pennell (2016) and Tansey et al. (2017). Relatedly and recognizing a potential for increased respondent burden, it is essential that the goals of the survey and potential benefits are clearly stated in the consent form. For example, after a particular disaster several research organizations may try to collect data from the same affected populations. In other situations, some respondents may be under the impression that survey participation could be tied with humanitarian or governmental assistance (see de Jong, K.C., and Pennell (2016). In situations where field enumerators come from the disaster-affected communities, it is also important to understand how this may affect their mental health and what services can be put in place to support them.

Relatedly, socio-economic data can be collected through participatory mapping and enumeration (see Gaillard et al. (2016) for more information on quantitative participatory methods). Instead of relying on external data collectors, dwellers can draw maps of risky/affected neighbourhoods (see the example of Legazpi City in the Philippines, in Jackson and Aboagye (2015). Such initiatives are only possible by working closely and in coordination with local communities and other stakeholders. Participatory mapping enables the active participation of communities to share their knowledge about volcanic hazards, as well as it allows them to visualize risks and thus be better prepared in the event of a disaster. This process can be completed by participatory enumeration conducted by trained members of the communities and prior discussions with community members to institutionalize their co-production of data. In the aftermath of a disaster, they are more likely to be in a capacity to collect socio-economic data from affected households.

At the macroeconomic level, challenges that arise are due to the limited availability of physical data (see Section 2) and the aggregation of data using different methodologies. As highlighted by Hallegatte and Przyluski (2010), the scope and precision of disaster related data has improved in the 1990s, which casts doubts on long-term time series or panel data studies. In addition to this, because large volcanic disasters are scarce, it is more complicated to actually capture their macroeconomic impact in respect to other macroeconomic shocks.

# 7 Conclusion

In this article, we raised knowledge gaps and methodological challenges in this under-explored topic. Mobilizing the literature in the economics of disasters, environmental and natural resource economics, economics of risk and uncertainty, experimental economics and development economics, we reviewed the concepts and the few research articles focusing on whether and how economies are affected by volcanic activity. There are not only many costs to assess that require the methods developed by economists in order to get the full picture of the distributions of volcanic losses, but also a variety of suspected effects and mechanisms to investigate in Microeconomics and Macroeconomics. In particular, the fact that most volcanic losses are localized around volcanoes and that this risk is made tangible in the landscape by easily recognizable and imposing landforms makes it likely that volcanic risk contributes to the creation of poverty traps at the foot of volcanoes. By highlighting research gaps in the "Economics of volcanoes", we provided future avenues of research that will address policy-relevant debates in the context of greater focus on risk mitigation, adaptation and resilience policies in facing natural disasters.

In that sense, this article does not only come within the profuse strands of literature reviews on natural disasters (Hallegatte and Przyluski, 2010; Cavallo, Noy et al., 2011; Sawada and Takasaki, 2017), it also follows up on an issue raised by many empirical studies. Facing data challenges relative to both the low frequency of large disasters and the lack of data on smaller adverse natural events, empiricists in search for variability in their data have to choose between i) cross-country panel settings in which they can have sufficient enough prevalence of one type of natural disaster, but many core institutional and geographic features may be correlated with it (Hsiang and Jina, 2014; Kocornik-Mina et al., 2015), ii) the same settings but within a single country and with fewer chance to be able to disaggregate the effect of one type of natural disaster especially if the country is small and the event is rare (Anttila-Hughes and Hsiang, 2013; Boustan et al., 2018), and iii) case studies of a specific major disaster (Hornbeck, 2012; Deryugina, Kawano, and Levitt, 2018). By discussing concepts of economic analysis in the case of volcanic risk, our work highlights that the varying characteristics of each type of disaster may lead to specific effects that should make one as reluctant to aggregate all disasters into a unique variable in an empirical model, as worried about missing variables.

## References

Adamov, A., and V.K. S. 2017. “The destructive power of volcanic ash fall: quantifying volcanic risks will improve insurability and strengthen urban resilience.” Working paper, Swiss Re Institute.

Ager, P., K. Eriksson, C.W. Hansen, and L. Lønstrup. 2019. “How the 1906 San Francisco Earthquake Shaped Economic Activity in the American West.” Working paper, National Bureau of Economic Research.

Albala-Bertrand, J.M. 1993. “Natural disaster situations and growth: A macroeconomic model for sudden disaster impacts.” *World Development* 21:1417–1434.

Anttila-Hughes, J., and S. Hsiang. 2013. “Destruction, disinvestment, and death: Economic and human losses following environmental disaster.” Working paper.

Arvan, L., and D. Nickerson. 2006. “Private Investment, Public Aid and Endogenous Divergence in the Evolution of Urban Neighborhoods.” *The Journal of Real Estate Finance and Economics* 32:83–100.

Auffret, P. 2003. *High consumption volatility: The impact of natural disasters?*. The World Bank.

Blumenstock, J.E., N. Eagle, and M. Fafchamps. 2016. “Airtime transfers and mobile communications: Evidence in the aftermath of natural disasters.” *Journal of Development Economics* 120:157 – 181.

Bohra-Mishra, P., M. Oppenheimer, and S.M. Hsiang. 2014. “Nonlinear permanent migration response to climatic variations but minimal response to disasters.” *Proceedings of the National Academy of Sciences* 111:9780–9785.

Boustan, L., M. Kahn, P. Rhode, and M.L. Yanguas. 2018. “The Effect of Natural Disasters on Economic Activity in US Counties: A Century of Data.” Working paper, UCLA California Center for Population Research.

Brown, S., S. Loughlin, R. Sparks, and C. Vye-Brown. 2015. “Global volcanic hazards and risk: Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015.” *Global Volcano Model and the International Association of Volcanology and Chemistry of the Earthâs Interior*, pp. .

Browne, M.J., and R.E. Hoyt. 2000. “The Demand for Flood Insurance: Empirical Evidence.” *Journal of Risk and Uncertainty* 20:291–306.

Caruso, G.D. 2017. “The legacy of natural disasters: The intergenerational impact of 100 years of disasters in Latin America.” *Journal of Development Economics* 127:209 – 233.

Cavallo, E., S. Galiani, I. Noy, and J. Pantano. 2013. "Catastrophic natural disasters and economic growth." *Review of Economics and Statistics* 95:1549–1561.

Cavallo, E., I. Noy, et al. 2011. "Natural disasters and the economyâa survey." *International Review of Environmental and Resource Economics* 5:63–102.

Champ, P.A., K.J. Boyle, T.C. Brown, and L.G. Peterson. 2003. *A primer on nonmarket valuation*, vol. 3. Springer.

Choumert-Nkolo, J., and P. Phélinas. 2019. "Natural disasters, land and labour." *European Review of Agricultural Economics*, 07, pp. .

Coate, S. 1995. "Altruism, the Samaritan's Dilemma, and Government Transfer Policy." *The American Economic Review* 85:46–57.

Coffman, M., and I. Noy. 2012. "Hurricane Iniki: measuring the long-term economic impact of a natural disaster using synthetic control." *Environment and Development Economics* 17:187–205.

Crespo Cuaresma, J., J. Hlouskova, and M. Obersteiner. 2008. "Natural disasters as creative destruction? Evidence from developing countries." *Economic Inquiry* 46:214–226.

Cunado, J., and S. Ferreira. 2014. "The macroeconomic impacts of natural disasters: the case of floods." *Land Economics* 90:149–168.

De Groeve, T., K. Poljansek, and D. Ehrlich. 2013. "Recording Disaster Losses: Recommendations for a European approach." Working paper, European Commission Joint Research Centre.

de Jong, J., H. K.C., and S. Pennell. 2016. "Ethical Considerations. Guidelines for Best Practice in Cross-Cultural Surveys." Working paper, Ann Arbor, MI: Survey Research Center, Institute for Social Research, University of Michigan.

D'Ercole, R. 1989. "La catástrofe del Nevado del Ruiz, ¿Una enseñanza para el Ecuador? El caso del Cotopaxi." *Estudios de Geografía* 2:5–32, Corporación Editora Nacional, Riesgos Naturales en Quito.

Dercon, S. 2004. "Growth and shocks: evidence from rural Ethiopia." *Journal of Development Economics* 74:309 – 329.

Deryugina, T., G. Heutel, N.H. Miller, D. Molitor, and J. Reif. Forthcoming. "The mortality and medical costs of air pollution: Evidence from changes in wind direction." *American Economic Review*, pp. .

Deryugina, T., L. Kawano, and S. Levitt. 2018. “The Economic Impact of Hurricane Katrina on Its Victims: Evidence from Individual Tax Returns.” *American Economic Journal: Applied Economics* 10:202–33.

Do, Q., and L. Iyer. 2008. “Land Titling and Rural Transition in Vietnam.” *Economic Development and Cultural Change* 56:531–579.

Doucouliagos, C., T. Stanley, and M. Giles. 2012. “Are estimates of the value of a statistical life exaggerated?” *Journal of Health Economics* 31:197 – 206.

Elbers, C., J.W. Gunning, and B. Kinsey. 2007. “Growth and Risk: Methodology and Micro Evidence.” *World Bank Economic Review* 21:1–19.

Ewert, J.W., and C.J. Harpel. 2004. “In harmâs way: population and volcanic risk.” *Geotimes* 49:14–17.

Fafchamps, M. 1992. “Cash Crop Production, Food Price Volatility, and Rural Market Integration in the Third World.” *American Journal of Agricultural Economics* 74:90–99.

—. 1993. “Sequential Labor Decisions Under Uncertainty: An Estimable Household Model of West-African Farmers.” *Econometrica* 61:1173–1197.

Fafchamps, M., and F. Gubert. 2007. “The formation of risk sharing networks.” *Journal of Development Economics* 83:326 – 350, Papers from a Symposium: The Social Dimensions of Microeconomic Behaviour in Low-Income Communities.

Fafchamps, M., and A.R. Quisumbing. 2007. “Chapter 51 Household Formation and Marriage Markets in Rural Areas.” In T. P. Schultz and J. A. Strauss, eds. *Handbook of Development Economics*. Elsevier, vol. 4 of *Handbook of Development Economics*, pp. 3187 – 3247.

Faurie, C., C. Mettling, M.A. Bchir, D.S. Hadmoko, C. Heitz, E.D. Lestari, M. Raymond, and M. Willinger. 2016. “Evidence of genotypic adaptation to the exposure to volcanic risk at the dopamine receptor DRD4 locus.” *Scientific reports* 6:37745.

Felbermayr, G., and J. Gröschl. 2014. “Naturally negative: The growth effects of natural disasters.” *Journal of development economics* 111:92–106.

Fomby, T., Y. Ikeda, and N. Loayza. 2009. *The growth aftermath of natural disasters*. The World Bank.

Gaddis, E.B., B. Miles, S. Morse, and D. Lewis. 2007. “Full-cost accounting of coastal disasters in the United States: Implications for planning and preparedness.” *Ecological Economics* 63:307 – 318, Ecological Economics of Coastal Disasters.

Gaillard, J., J.R. Cadag, A. Gampell, K. Hore, L. Le Dé, and A. McSherry. 2016. "Participatory numbers for integrating knowledge and actions in development." *Development in Practice* 26:998–1012.

Gill, J.C., and B.D. Malamud. 2014. "Reviewing and visualizing the interactions of natural hazards." *Reviews of Geophysics* 52:680–722.

Global Volcanism Program. 2013. "Volcanoes of the World, v.4.8.2." Venzke, E (ed.). Smithsonian Institution, Available online at: https://doi.org/10.5479/si.GVP.VOTW4-2013 (accessed 09 Sep 2019).

Graff Zivin, J., and M. Neidell. 2012. "The Impact of Pollution on Worker Productivity." *American Economic Review* 102:3652–73.

Grislain-Letrémy, C. 2018. "Natural Disasters: Exposure and Underinsurance." *Annals of Economics and Statistics*, pp. 53–83.

Gröger, A., and Y. Zylberberg. 2016. "Internal Labor Migration as a Shock Coping Strategy: Evidence from a Typhoon." *American Economic Journal: Applied Economics* 8:123–53.

Guha-Sapir, D., R. Below, and P. Hoyois. 2019. "EM-DAT: The CRED/OFDA International Disaster Database." UniversitÃ© Catholique de Louvain, Brussels, Belgium., Available online at: http://emdat.be/ (accessed 10 Sep 2019).

Halkos, G., and A. Zisiadou. 2018. "Reporting the natural environmental hazards occurrences and fatalities over the last century.", pp. .

Hallegatte, S., and P. Dumas. 2009. "Can natural disasters have positive consequences? Investigating the role of embodied technical change." *Ecological Economics* 68:777–786.

Hallegatte, S., and V. Przyluski. 2010. *The economics of natural disasters: concepts and methods*. The World Bank.

Hansell, A., C. Horwell, and C. Oppenheimer. 2006. "The health hazards of volcanoes and geothermal areas." *Occupational and environmental medicine* 63:149–125.

Hearne, R.R., and Z.M. Salinas. 2002. "The use of choice experiments in the analysis of tourist preferences for ecotourism development in Costa Rica." *Journal of environmental management* 65:153–163.

Hochrainer, S. 2009. *Assessing the macroeconomic impacts of natural disasters: are there any?*. The World Bank.

Hornbeck, R. 2012. "The Enduring Impact of the American Dust Bowl: Short- and Long-Run Adjustments to Environmental Catastrophe." *American Economic Review* 102:1477–1507.

Hsiang, S.M., and A.S. Jina. 2014. "The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones." NBER Working Papers No. 20352, National Bureau of Economic Research, Inc, Jul.

Jack, W., and T. Suri. 2014. "Risk Sharing and Transactions Costs: Evidence from Kenya's Mobile Money Revolution." *American Economic Review* 104:183–223.

Jackson, E., and D. Aboagye. 2015. ""Why should we wait?": Mapping for the next disaster." AidData's Blog, Available online at: https://www.aiddata.org/blog/why-should-we-wait-mapping-for-the-next-disaster (accessed 30 MAy 2019).

Kelman, I., and T.A. Mather. 2008. "Living with volcanoes: the sustainable livelihoods approach for volcano-related opportunities." *Journal of Volcanology and Geothermal Research* 172:189–198.

Kocornik-Mina, A., T.K. McDermott, G. Michaels, and F. Rauch. 2015. "Flooded cities." GRI Working Papers No. 221, Grantham Research Institute on Climate Change and the Environment, Dec.

Lavigne, F., B. De Coster, N. Juvin, F. Flohic, J.C. Gaillard, P. Texier, J. Morin, and J. Sartohadi. 2008. "People's behaviour in the face of volcanic hazards: Perspectives from Javanese communities, Indonesia." *Journal of Volcanology and Geothermal Research* 172:273–287.

Leiter, A.M., H. Oberhofer, and P.A. Raschky. 2009. "Creative disasters? Flooding effects on capital, labour and productivity within European firms." *Environmental and Resource Economics* 43:333–350.

Ligon, E., and L. Schechter. 2003. "Measuring Vulnerability." *Economic Journal* 113:C95–C102.

Maccini, S., and D. Yang. 2009. "Under the Weather: Health, Schooling, and Economic Consequences of Early-Life Rainfall." *American Economic Review* 99:1006–26.

Macours, K. 2013. "Volatility, agricultural risk, and household poverty: micro-evidence from randomized control trials." *Agricultural Economics* 44:79–84.

Martí, J., and G.G. Ernst. 2009. *Volcanoes and the Environment*. Cambridge University Press.

Melecky, M., and C. Raddatz. 2014. "Fiscal responses after catastrophes and the enabling role of financial development." *The World Bank Economic Review* 29:129–149.

Melecky, M., and C.E. Raddatz. 2011. "How Do Governments Respond after Catastrophes? Natural-Disaster Shocks and the Fiscal Stance." Working paper, World Bank Policy Research Working Paper No. 5564.

Mohan, P.S., B. Ouattara, and E. Strobl. 2018. "Decomposing the macroeconomic effects of natural disasters: A national income accounting perspective." *Ecological economics* 146:1–9.

Newhall, C.G., and S. Self. 1982. "The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism." *Journal of Geophysical Research: Oceans* 87:1231–1238.

Noy, I. 2009. "The macroeconomic consequences of disasters." *Journal of Development Economics* 88:221 – 231.

Noy, I., and T.B. Vu. 2010. "The economics of natural disasters in a developing country: The case of Vietnam." *Journal of Asian Economics* 21:345–354.

Paton, D., M. Millar, and D. Johnston. 2001. "Community resilience to volcanic hazard consequences." *Natural hazards* 24:157–169.

Raddatz, C. 2009. *The wrath of God: macroeconomic costs of natural disasters*. The World Bank.

Raschky, P.A. 2008. "Institutions and the losses from natural disasters." *Natural hazards and earth system sciences* 8:627–634.

Raschky, P.A., R. Schwarze, M. Schwindt, and F. Zahn. 2013. "Uncertainty of Governmental Relief and the Crowding out of Flood Insurance." *Environmental and Resource Economics* 54:179–200.

Rosenzweig, M.R., and H.P. Binswanger. 1993. "Wealth, Weather Risk and the Composition and Profitability of Agricultural Investments." *The Economic Journal* 103:56–78.

Rosenzweig, M.R., and O. Stark. 1989. "Consumption Smoothing, Migration, and Marriage: Evidence from Rural India." *Journal of Political Economy* 97:905–926.

Rosenzweig, M.R., and K.I. Wolpin. 1993. "Credit Market Constraints, Consumption Smoothing, and the Accumulation of Durable Production Assets in Low-Income Countries: Investments in Bullocks in India." *Journal of Political Economy* 101:223–244.

Ruiz, C., and B. Hernández. 2014. "Emotions and coping strategies during an episode of volcanic activity and their relations to place attachment." *Journal of environmental psychology* 38:279–287.

Sawada, Y., and Y. Takasaki. 2017. "Natural Disaster, Poverty, and Development: An Introduction." *World Development* 94:2 – 15.

Schwefer, M. 2018. “Sitting on a Volcano: Domestic Violence in Indonesia Following Two Volcano Eruptions.” ifo Working Paper Series No. 263, ifo Institute - Leibniz Institute for Economic Research at the University of Munich.

Sigmundsson, F., S. Hreinsdóttir, A. Hooper, T. Árnadóttir, R. Pedersen, M.J. Roberts, N. Óskarsson, A. Auriac, J. Decriem, P. Einarsson, et al. 2010. “Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption.” *Nature* 468:426.

Simkin, T. 1993. “Terrestrial volcanism in space and time.” *Annual Review of Earth and Planetary Sciences* 21:427–452.

Simkin, T., and L. Siebert. 1984. “Explosive eruptions in space and time: durations, intervals, and a comparison of the worldâs active volcanic belts.” *Explosive Volcanism: Inception, Evolution, and Hazards*, pp. 110–121.

—. 1994. “Volcanoes of the World 2nd Edition.” *Smithsonian Institution, Geosciences Press Inc.(349 pp.)*, pp. .

Simkin, T., L. Siebert, and R. Blong. 2001. “Volcano fatalities–lessons from the historical record.” *Science* 291:255.

Skidmore, M., and H. Toya. 2002. “Do natural disasters promote long-run growth?” *Economic inquiry* 40:664–687.

Small, C., and T. Naumann. 2001. “The global distribution of human population and recent volcanism.” *Environmental Hazards* 3:93 – 109.

Stark, O., and R.E.B. Lucas. 1988. “Migration, Remittances, and the Family.” *Economic Development and Cultural Change* 36:465–481.

Stephane, V. 2018. “Three essays on the economic impact of natural disasters.” PhD dissertation, University of Clermont Auvergne, Clermont-Ferrand, France.

Strobl, E. 2012. “The economic growth impact of natural disasters in developing countries: Evidence from hurricane strikes in the Central American and Caribbean regions.” *Journal of Development economics* 97:130–141.

Tanguy, J.C., C. Ribière, A. Scarth, and W. Tjetjep. 1998. “Victims from volcanic eruptions: a revised database.” *Bulletin of volcanology* 60:137–144.

Tansey, C.M., J. Anderson, R.F. Boulanger, L. Eckenwiler, J. Pringle, L. Schwartz, and M. Hunt. 2017. “Familiar ethical issues amplified: how members of research ethics committees describe ethical distinctions between disaster and non-disaster research.” *BMC medical ethics* 18:44.

Toya, H., and M. Skidmore. 2007. "Economic development and the impacts of natural disasters." *Economics Letters* 94:20 – 25.

Udry, C. 1994. "Risk and Insurance in a Rural Credit Market: An Empirical Investigation in Northern Nigeria." *The Review of Economic Studies* 61:495–526.

UNDRR. ???? "DesInventar databases." Sendai Framework For Disaster Risk Reduction, Available online at: https://www.desinventar.net/ (accessed 11 Sep 2019).

United Nations. Secretary General. 2016. "Report of the Open-ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction." 41 p. Available online at: https://digitallibrary.un.org/record/852089 (accessed 09 Sep 2019).

view. 2005. "Some Aspects of the Economics of Catastrophe Risk Insurance." CESifo Working Paper Series No. 1409, CESifo Group Munich.

Wilson, T., J. Cole, S. Cronin, C. Stewart, and D. Johnston. 2011. "Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery." *Natural Hazards* 57:185–212.

Witham, C.S., and C. Oppenheimer. 2005. "Mortality in England during the 1783–4 Laki Craters eruption." *Bulletin of Volcanology* 67:15–26.

Yang, D. 2008. "Risk, Migration, and Rural Financial Markets: Evidence from Earthquakes in El Salvador." *Social Research* 75:955–992.