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The Economics of Volcanoes

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Abstract:

Volcanic hazards pose a potential threat to 8% of the world's population, yet the economic literature on their short- and long-term consequences on household behavior and economic development is still in its infancy. In this article, we present the state of the literature and highlight knowledge gaps and methodological challenges inherent to the economic analysis of volcanic hazards and disasters. We first present the physical aspects of volcanic activity and describe available physical data. We then examine the concepts related to cost assessment of volcanic disasters. Finally, we discuss key micro and macroeconomic 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 aimed at mitigating natural hazards and disasters.

Keywords:

Natural Disaster; Adaptation; Risk; Hazard; Resilience; Economics

JEL codes:

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1. Introduction

It is estimated that between 8% and 14.5% of the world's population is currently exposed to a potential volcanic hazard (Freire et al., 2019)[4] and according to Ewert and Harpel (2004), this figure is expected to increase in the future. Sustained population growth, increasing migration to areas (both urban and rural) in close proximity to volcanoes, and the possibility of larger eruptions to come are the main drivers of this trend. The rise in potential exposure will occur mainly in low-to-middle-income countries (LMICs), where a significant part of the population has limited resources but where most active volcanoes are located (see Appendix A). The so-called "Ring of Fire" circles the Pacific Ocean along the Pacific coast of the Americas and Southeast Asia; the Great Rift Valley is a 6,000-mile crack stretching from Lebanon to Mozambique that continues to expand. As a result, many large cities in LMICs, including Mexico City, Manila, Guatemala City, San Salvador, Managua and Quito, are under persistent threat of a volcanic eruption.

Eruptions can be highly destructive. Volcanic events have killed approximately 98,000 people and affected about 5.6 million people worldwide during the twentieth century (Witham, 2005). The most common consequences of volcanic events include loss of life, respiratory illness, and severe economic losses, including destruction or damage to housing, infrastructure, and land. Compared to the excess mortality triggered by other disasters, volcanic fatality counts might appear marginal. However, rare volcanic disasters such as the 2018 twin eruptions of the Volcán de Fuego in Guatemala and of the Anak Krakatau volcano in Indonesia, which together rendered the 2018 death toll from volcanoes higher than that of the previous eighteen years combined (CRED, 2019), are forceful reminders of the threat of volcanic activity. Moreover, more moderate but repeated volcanic hazards continue affecting local populations worldwide. Indeed, there are approximately twenty volcanoes at any given time around the world emitting ongoing eruptions (GVP, 2020).

Despite this risk proving economically significant at both the local and global scales,[5] the economic analysis of volcanic hazards is still in its infancy. Indeed, in the economic literature there are very few contributions on volcanoes, compared to the number of contributions in other physical and social sciences, as well as relative to the economic literature on other natural hazards (see Appendix B). This article contributes to the literature by highlighting this dearth in research and calls for the increased study of volcanic hazards in the economic literature.

A volcano is a geological structure formed when molten rock, ash and gases are emitted through a rupture of the Earth's surface. From an economic perspective, volcanoes can essentially be approached through two lenses: 'natural disaster' risk and 'amenity' (e.g., touristic activity and geothermal energy); however, this second aspect exceeds the scope of this paper[6] since our emphasis is on hazards and disasters. In this article, we highlight knowledge gaps and methodological challenges in this under-explored subject. Mobilizing the literature of the economics of disasters, environmental and natural resource economics, economics of risk and uncertainty, and development economics, we review the

[4] The first figure is based on the population living within 100 km of a volcano with at least one significant eruption, the second is based on the population living within 100 km of a volcano that has erupted during the Holocene period (the last 10,000 years to present). The 100 km radius represents a zone that can potentially suffer direct damages from a volcanic hazard (Freire et al., 2019).

[5] See, for instance, the 2010 Eyjafjallajokull explosive eruption that had global impacts on air traffic (Sigmundsson, 2010).

[6] The interested reader can consult Kelman and Mather (2008), Hearne and Salinas (2002) and Musafili et al. (2019).

concepts and the few research articles focusing on whether and how economies are affected by volcanic hazards and disasters. We conclude that, in order to get the full picture of the distributions of volcanic losses, there are many costs to assess that require the methods developed by economists, as well as a variety of suspected effects and mechanisms to investigate in both micro- and macroeconomics. In particular, the fact that most volcanic losses are localized around volcanoes 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 needed to address natural disasters. In that sense, this article not only comes within the vast literature reviews on natural disasters (Hallegatte and Przyluski, 2010; Cavallo and Noy, 2011; Sawada and Takasaki, 2017), it also follows up on an issue raised by many empirical studies. Facing data challenges relative to the lack of both frequency of large disasters and data on smaller adverse natural events, empiricists in search for variability in their data are forced to choose between i) cross-country panel settings which provide sufficient prevalence of one type of natural disaster, that may be correlated with many core institutional and geographic features (Hsiang and Jina, 2014; Kocornik Mina et al., 2015), ii) the same settings within a single country and thus fewer chances to disaggregate the effect of one type of natural disaster, especially if the country is small and the event is rare (Anttila Hughes et al., 2013; Boustan et al., 2018), or iii) case studies of a specific major disaster with limited external validity (Hornbeck, 2012; Deryugina et al., 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 one would be concerned about missing variables.

The rest of the article is organized as follows. Firstly, Section 2 presents the physical aspects of volcanic activity and describes available physical data. Section 3 examines what costs should be associated with an eruption and how to assess them. In Sections 4 and 5, we discuss the suspected transmission channels at stake at the microeconomic and macroeconomic levels, respectively, and review the scant evidence on whether and how volcanoes affect welfare and development outcomes. Section 6 identifies relevant methodological and data challenges.

2. Volcanic hazards, volcanic risks and volcanic disasters

According to the UNDDR glossary,[7] a hazard is "a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation". Many hazardous processes including earthquakes, volcanic eruptions, tsunamis, and landslides have a geological origin and are part of the Earth's history. For a hazard to turn into a disaster, populations 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 resources". Compared to hazard, the concept of risk introduces the idea of probability: "disaster risk is the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time,

[7] https://www.undrr.org/terminology (last consulted on 15/04/2020)

determined probabilistically as a function of hazard, exposure, vulnerability and capacity". Hence, the economic implications of a natural event such as an eruption will depend on both the characteristics of the physical hazard and the population and assets that are exposed to it.

In this section, we provide an overview of the spatial and temporal heterogeneity and uncertainty inherent to volcanism as a geological process, in order to illustrate the challenges of defining volcanic risk in an economic framework.

2.1. Characteristics of volcanic activity

The planet's eruptive volcanoes are recorded in the database of the Smithsonian Institution's Global Volcanism Program. This database lists 1,428 volcanoes that are thought to have had at least one eruption during the Holocene period. Among these, 443 active volcanoes have given rise to 3,445 observed eruptions since the beginning of the twentieth century.[8]

There is great heterogeneity in terms of physical characteristics, intensity, length and damages resulting from what is called a volcanic eruption. Effusive eruptions release lava that follows topographic depressions whereas explosive eruptions project gases and ash, as well as solid rock fragments, that disperse in the atmosphere under the effects of wind. Explosive eruptions are the most dangerous as 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. Explosive eruptions also usually affect larger areas because they can throw ashes up to several kilometres around a volcano. These eruptions are also the most frequent and, according to Small (2001), most people exposed to volcanic hazard are exposed to explosive rather than effusive eruptions. Lahars or mud flows are another type of volcanic event that originates either from the heat of an eruption that melts snow or ice or that are the result of torrential rains that fall on volcanic deposits. These landslides, which devastate everything in their path and can travel for miles, are an extremely dangerous phenomenon.

Each individual eruption has its own characteristics: In particular, eruptions vary in their intensity and temporal (duration) scales. The magnitude of volcanic eruptions is usually measured using the volcanic explosivity index (VEI) introduced by Newhall and Self (1982). This index indicates both the amount of mass ejected during an eruption and the size of the eruption column, which ranges from zero (gentle eruption) to eight (mega-colossal eruption). [9]

Eruptions may also trigger by-disasters. According to Gill (2014), volcanic eruptions are the natural risk that generates the most secondary risks, which include landslides, ground collapse, and wildfires.

Even with the benefit of current technology, and despite the high level of surveillance of many volcanoes worldwide, the probability of eruption associated with each of the possible volcanic events for each location is far from certain. Simkin and Siebert (1984) emphasized that during the last 10,000 years (Holocene), 17 of the 21 largest historical eruptions have occurred at volcanoes that had experienced no previous eruptions.

[8] https://volcano.si.edu/list_volcano_holocene.cfm (last consulted on 30/12/2019); https://volcano.si.edu/search_eruption.cfm (last consulted on 30/12/2019).

[9] This index indicates eruptions rated at VEI 1 produce between 0.0001 and 0.001 cubic kilometres of tephra ejected. Each step in the scale represents an explosivity increase of tenfold. As far as duration is concerned, the Smithsonian Institution's Global Volcanism Program reports eruptions lasting from a few days to several years.

2.2. Measuring the impacts of volcanic activity

Volcanic risk assessment is a challenging endeavour because the heterogeneity of volcanic hazards and the diversity of socioeconomic outcomes that can result from them imply that the selection of indicators for volcanic activity is critical in empirical economic research.

Volcanic events are the best exogenous measure of volcanic hazards. They can be captured by three indicators: the frequency of events over a given period, the magnitude of volcanic eruptions, and the duration of an eruption. These physical indicators do not depend on a country's level of development. However, they are poorly correlated with the potential human and economic impacts of an event. As a result, in the literature, volcanic activity is typically measured through the intensity of its effect (e.g., mortality, economic costs of damages), although these effects obviously have an endogenous component. Different databases exist that record the intensity of the impact in terms of the damage of volcanic activity (Simkin and Siebert, 1994; Tanguy et al., 1998; Witham, 2005; EM-DAT, CRED, 2010,[10] DesInventar[11]).

Among the sources just referenced, the emergency Events Database (EM-DAT) is the only open access database which provides the intensity of the impact of natural disasters worldwide.[12] 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 various international research institutions. As far as volcanic hazards are concerned, however, many researchers have pointed out a number of deficiencies and measurement errors.

First, only disaster events are recorded. To be included in EM-DAT, a disaster must have killed ten or more persons, affected one hundred or more people, caused a state of emergency to be declared, or provoked a call for international assistance. This means that small volcanic events and events occurring at a limited geographical scale are not recorded. However, repeated small or medium events such as ash falls can seriously affect both domestic and daily productive activities, and may have long-term health impacts and significant economic consequences (Choumert-Nkolo and Phélinas, 2020). Some affected people may not be able to restart their former economic activities because their capital (land and livestock) has been destroyed or seriously damaged.

Second, different historical records of casualties caused by volcanic events show considerable inconsistencies in the number of victims (Tanguy 1998, Simkin et al., 2001, Witham 2005). There are several 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 et al., 2001; Witham, 2005). Some effects of a shock may become evident only over the long term. For instance, some people may die well after an initial eruption from respiratory illness, injuries caused by the event, or even later by indirect food shortage, malnutrition, or poor housing and sanitary conditions in evacuation areas (Hansell et al., 2006; Halkos and Zisiadou, 2018).[13] Although records for

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[10] https://www.emdat.be/

[11] https://www.desinventar.net/whatisdesinventar.html

[12] DesInventar is a database comparable to EM-DAT but mainly covers Latin American countries and, to a lesser extent, Asian and African countries. For an exhaustive comparison of Desinventar and EM-DAT, see De Groeve et al. (2013).

[13] Note that the final fatality figures in EM-DAT may be updated even long after the disaster has occurred.

recent events are/tend to be more accurate, the poor reliability of historical data raises the problem of time series consistency.

In addition, according to Witham (2005), the term "affected" is problematic and confusing because people are affected in very different ways. However, there are no standards for collecting all these aspects and the content of the term appears to have changed over time. It initially referred primarily to evacuees and those rendered homeless. Later on, it included persons under alert and those seriously affected by ash falls.

Furthermore, the accuracy of the numbers of killed/injured/affected/missing persons depends both on a country's level of development and the location of the event itself. Persons living in remote areas and in LMICs are less likely 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 may be lacking. The amount of economic loss also depends on the country's GDP per capita. The magnitude of economic losses is expected to be greater in richer countries because more private property and greater assets are at risk, and public infrastructure is more developed.

Finally, routine data collection rests with national and local authorities. The numbers reported are highly sensitive figures and could be tainted with errors reflecting socio-political considerations or the desire 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's level of income and thus its economic damage. Furthermore, large measurement errors concerning minor events give a misleading indication of the economic risk for populations living near a volcano. Such data deficiencies limit volcanic risk assessment by scientists and policy makers and are an obstacle to understanding response, adaptation, and resilience to the exposure of a volcanic hazard.

3. What are the costs of volcanic hazards?

There is large interest among academics, insurance companies, and public authorities in charge of risk management and post-disaster recovery in measuring the economic costs of natural disasters. Yet despite a wide spectrum of methodological approaches designed to assess these costs, not much is known about them. In this section, we provide a conceptual overview around 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), and secondly, by offering suggestions for future research.

3.1. Direct and indirect costs

Volcanic events generate significant natural, social, human and built capital losses. This section provides an overview of commonly used concepts in cost assessment. The conceptual framework is no different from that related to natural disasters (See Hallegatte and Przyluski, 2010, for a thorough overview of the literature).

Direct losses are immediate consequences of a physical volcanic event. Loss of built capital, human capital and agricultural assets are major components of these direct losses. Built capital notably includes buildings, dwellings, schools, energy and road infrastructure, telecommunications, water systems, etc. Direct losses are divided between market and non-market losses. On the one hand, prices can be observed for market losses and typically include the damage or destruction of assets, whose value can be imputed through reparation or replacement costs. Yet imputing the monetary value of these losses is far from straightforward, and existing methods do not account for the distributional impacts of such capital losses (Gaddis et al., 2007). Moreover, since existing methods are based on market prices, they are subject to a series of constraints which are context specific such as the existence of informal housing markets or other missing markets. On the other hand, prices can't easily be observed for non-market losses, which can include damage or destruction of cultural and historical sites, ecosystems, and health impacts.[14] The economic literature provides a wide range of tools to estimate the economic value of non-market goods and services, but many debates persist with respect to the terminologies and tools used (see non-market valuation techniques, Champ et al., 2003; statistical value of human life, Doucouliagos et al., 2012). Indirect losses arise in the aftermath of a volcanic event. As there is no consensus on the typology of these indirect losses, Hallegatte and Przyluski (2010) suggest the use of the following criteria: "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 itself." The authors add that "With 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." Indirect losses can take the form of both market and non-market losses, including loss of earnings or employment as a result of road damage or a decrease in consumer demand, as well as short-term and long-term impacts on macroeconomic aggregates such as poverty rates, gross domestic product and government expenditure. (These macroeconomic effects can also be referred to as secondary effects, Martí and Ernst, 2008). See further discussions on these macroeconomic costs in Section 5.

Indirect costs are a major component of the total cost of natural disasters (Hallegatte and Przyluski, 2010; Martí and Ernst, 2008) but most assessments are made based on direct costs, which thus leads to a general underestimation of the costs of natural disasters. As a matter of fact, costs reported in the aftermath of a disaster typically refer to more tangible costs, whereas intangible costs are mostly reported in non-monetary terms (e.g., the number of affected persons).

3.2. Future research and methodological challenges

The field of economics allows us to quantify the losses suffered by a community or a country as a result of volcanic events beyond those caused by physical destruction. Nevertheless, although they affect millions of people worldwide (see Section 2), there remain significant research and knowledge gaps on the total economic costs of volcanic events. As seen previously, cost assessments of volcanic events are complex since damages are spread out at different magnitudes, as well as temporal[15] and spatial

[14] Halliday et al. (2019) explored variation in air quality generated by volcanic eruptions of the Kilauea in the state of Hawaii. They identified a strong correlation between volcanic emissions and air quality, and their analysis suggests that a one standard deviation in particulate pollution led to an increase of 23% to 36% in expenditures for emergency room visits caused by pulmonary outcomes. One illustration of non-market direct loss assessment is the valuation of economic services from forests that were destroyed by the 2018 eruption of the *Volcan de Fuego*, Guatemala (WB/ECLAC/PNUD, 2018).

[15] There can be significant heterogeneity in the intensity and duration of volcanic events, which may evolve over time. For instance, ash falls entail a cost in the aftermath of an event, but they can increase soil fertility in the long term (Lansing, 2001).

scales (sometimes in multiple countries). This subject therefore deserves further research efforts to better address responses to disasters and public policies involving volcanic hazards.

Firstly, cost assessment of volcanic events can only be derived by drawing from a wide range of the social and physical sciences and would therefore be better addressed by multidisciplinary teams. Secondly, volcanic events have the characteristics of both slow-onset and sudden-impact events (Martí and Ernst, 2008). This creates uncertainty about the temporal scope of cost assessment, creating a climate of uncertainty that can delay post-disaster reconstruction efforts. This relates to the issue of damages being at different magnitudes and temporal and spatial scales, which deserves further understanding through joint work between physical and medical scientists and social science researchers. Thirdly, cost assessment of volcanic events relies on having a baseline scenario and establishing a counterfactual to assess how the welfare of the community would have evolved in the absence of the volcanic event. In many cases, since volcanic events are very localized, it is not possible to build a counterfactual (see further discussion in Section 6.1 on socio-economic data). Finally, as with any other type of natural disaster, an obvious consequence of volcanic eruptions is the excess mortality and morbidity they can directly and indirectly cause. With the exception of Halliday et al. (2019), there is no study 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, effects that have been evidenced in the case of air pollution from anthropogenic sources (Graff Zivin and Neidell, 2012; Deryugina et al., 2019).

Cost assessment of volcanic events is a challenging exercise, both from a methodological and operational point of view. Still it is crucial for aiding policy makers when they have to decide what resources to provide in order to prepare for and mitigate future shocks. Cost assessment exercises, however, say little about the adaptive behavior and subsequent response of affected households to such shocks. In order to better inform risk management and post-disaster policies, economists should thus put more effort into understanding household behavior in the presence of volcanic hazard and in the aftermath of a disaster.

4. Household economics and volcanoes

Economic cost assessments fail to detail how volcanoes impact well-being. Aggregate losses that appear negligible may hide disastrous socioeconomic impacts when inflicted on deprived households, particularly where infrastructure and equipment were already insubstantial prior to an event. This issue appears all the more relevant when the concepts of development microeconomics are mobilized and the few micro studies available at this time are reviewed, as in this section. Moreover, the level of volcano-induced costs depends on how much effort people have invested in their own protection. According to the literature, part of the costs incurred may be attributable to the tendency of households to under-protect against volcanic hazards, making some of these costs avoidable.

4.1. Concepts

The analysis of the welfare losses inflicted on exposed households by a natural hazard uses concepts developed by two arrays of microeconomic studies in the literature. The first focuses on ex-post impacts when a shock occurs, and the second considers ex-ante strategies used by households to manage a risk in anticipation of a future shock. Given the location of volcanoes in LMICs, both ex-post and ex-ante effects can be analyzed in the light of the linkages between a volcanic risk, the poverty status of exposed individuals, and local markets inefficiencies. On the one hand, the endowment of household assets strongly defines the extent to which the household will be able to limit losses to their well-being when a disaster strikes (vulnerability) and to recover from them (resilience). For a high-vulnerability and low-resilience household, the occurrence of a natural disaster can render it unable to meet its basic needs and trapped in poverty, thus even more vulnerable and less resilient to a future shock. On the other hand, the threat of a disastrous event itself cannot be efficiently transferred away (missing or incomplete insurance market) from exposed households and small entrepreneurs. It affects their welfare and productive investment given their attitudes towards risk (Gollier and Pratt, 1996) and despite sophisticated but costly ex-ante self-insurance arrangements (Rosenzweig and Binswanger, 1993; Elbers et al., 2007). The responses of individuals to risk thus often perpetuate poverty.

For the poorest who have no access to financial markets and sacrifice allocative efficiency in order to smooth income fluctuations, ex-ante strategies can result in adopting additional productive activities with low marginal returns in order to diversify portfolios (Rosenzweig and Binswanger, 1993), increasing the share of 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 such strategies identified in cases of weather variability can only stand if capital stocks of both farms and off-farm businesses, as well as precautionary savings in the form of grains or livestock, are immune to the shock, a condition that is hardly expected when a volcanic disaster strikes.

As with asset sales, informal insurance mechanisms consisting in sharing risk with geographically close friends and relatives (Udry, 1994; Fafchamps and Gubert, 2007) may be seriously challenged around volcanoes because of the covariant nature of volcanic hazard. Instead, sending a household member to work away from an exposed area could be used for diversifying the kinship network and thus receiving remittances in case of a shock (Stark and Lucas, 1988; Rosenzweig and Stark, 1989; Gröger and Zylberberg, 2016). However, damaged infrastructure following a volcanic event can further limit the influx of support to the victims. Mobile technology may facilitate longer-distance assistance through phone-based transfers (Jack and Suri, 2014); still those with the greatest need are not necessarily those who receive such transfers (Blumenstock et al., 2016).

Therefore, household responses to a volcanic hazard are likely to best succeed in partial insurance, leading one to expect a decline in consumption, health, and education expenses when the uninsured volcanic event occurs, resulting in adverse and enduring impact on well-being (Dercon, 2004) that may be irreversibly transmitted to future generations and likely affect girls more than boys (Maccini and Yang, 2009). Being covariant and likely to trigger ex-ante coping strategies, the volcanic hazard is expected to cause household heavy losses (Ligon and Schechter, 2003; Elbers et al., 2007) that are unevenly distributed across households.

Population declines through outmigration from an area where a disaster has destroyed part of the capital stocks has been proven to be a predominant adjustment to re-establish labor market equilibrium (Hornbeck, 2012). Yet a volcanic event may not only cause residents to leave affected areas through the loss of income-generating opportunities. It may also counteract outmigration. Despite the destruction that can shrink a local housing market supply, relative land prices are likely to increase in close safer areas in the medium run after an event, pricing poor households out of these safer areas and encouraging them instead to stay in or move to affected areas (Boustan et al., 2018). Second, disasters make more costly the access to financing needed to source the substantial up-front costs that migration requires, resulting in credit constraints more likely to bind (Yang, 2008). Therefore, migration flows following volcanic events may worsen inequality as the rich move away from affected areas while the poor are left behind. In such a setting where households continue bearing the risk of uninsured losses, research has also identified demand-side causes for low levels of self-protection. For instance, public relief programs and private charities are a well-known zero-premium substitute for self-protection efforts. Called “charity hazard” (Browne and Hoyt, 2000), the crowding-out effect on self-protection depends on how much confidence exposed people have about receiving assistance in the event of a shock (Raschky et al., 2013). Fuelled by the extensive media coverage to be expected following an event as sensational as an erupting volcano, assistance to those affected can be rationally anticipated by residents when considering the possibility of disastrous volcanic hazards.

All of these strategies share the assumption that exposed individuals base their decisions on accurate knowledge of losses and probabilities. However, when considering an infrequent risk composed of incalculable combinations of hazards, people simply have no chance that their expectation is ultimately aligned with the real threat. Whatever the case, whether people perceive the volcanic risk and respond accordingly ex ante or whether they are fully uninsured and unprepared when a volcanic event occurs, the same conclusion emerges: volcanic activity is conducive to irreversible disinvestments.

4.2. Review of micro studies on volcanic risk

In line with the microeconomic literature, a limited pool of research articles provides evidence that volcanic hazard contributes to the creation of poverty traps at the foot of volcanoes. Together these articles point to a slower accumulation of physical (Faurie et al., 2016; Stéphane, 2018) and human (Caruso, 2017; Choumert-Nkolo and Phélinas, 2020) capital that can persist over generations (Caruso, 2017), as well as a decrease in social capital in poor communities (Stéphane, 2018) and among displaced people (Schwefer, 2018).

Stéphane (2018) showed that ex-ante effects on the accumulation of productive assets on Indonesian farms at risk of eruption can lead to a large capital stock gap. Also in Indonesia, Faurie et al. (2016) found that genetic differentiation favoring risk-averse attitudes among the most exposed inhabitants had occurred. Choumert-Nkolo and Phélinas (2020) provided evidence that households threatened by the Tungurahua volcano in Ecuador do not engage in diversifying their economic activities compared to unexposed households do. In line with this result, Caruso (2017) showed that volcanic eruptions that occurred in Latin America during the twentieth century have engendered long-lasting negative effects on the education and employment of affected individuals and their children, finding that some children attended school for a shorter period and were more likely to experience child labor if one of their parents was exposed to an eruption in his/her childhood. Among all natural disasters, Caruso (2017) found that volcanoes were responsible for the most devastating long-term effects on wealth.

In an Indonesian case by Schwefer (2018), alteration of parents' abilities to provide a nurturing environment for their children following eruptions was confirmed as a possible mechanism underlying the intergenerational transmission of the shock. The author attributed a decrease in household expenditures to the volcanic event, along with an increased likelihood for affected households to suffer from domestic violence, alcohol or drug abuse and lower emotional well-being.

In terms of social capital, Stéphane (2018) showed that interpersonal cooperation following an eruption tends to decrease with the homogeneity of wealth among members from Ecuadorian communities settled around the Tungurahua volcano. Accordingly, homogeneously poor households in affected communities may be even more vulnerable and less resilient to any future shock.

The only empirical results on migration decisions following an eruption come from Bohra Mishra et al. (2014) and are mixed. Still some suggested evidence can be found in Stéphane (2018) who showed that a positive correlation between the level of trust in public authorities by a household head living at risk of the Tungurahua volcano and the proportion of his/her children who remain in the same parish. This result is more worrisome in light of the author's previous findings that trust towards these institutions was fostered by the intensity of a past eruption. He argued that highly exposed individuals may reward the authorities for their past risk management with more confidence. Ultimately then, public efforts may have hampered outmigration from affected areas.

4.3. Future research

Since at-risk populations appear prone to underinvesting in protective measures against volcanic-induced damages and because of their high vulnerability and low resistance to shocks, the efficacy of public interventions, such as information campaigns, warning systems, and evacuation and relocation, intended to protect those at risk call for insights as to their efficacy or lack thereof. In particular, future research on location decisions and on how people process information on risk seems all the more relevant in the light of the history of volcanic crisis/crises that is replete with cases of residents refusing to evacuate or returning to an established risk area, and with controversies among stakeholders when receiving a warning (Fearnley et al., 2018; Barclay et al., 2019).

The first salient knowledge gap regards relocation decisions. Public policies assisting in moving a population may be desirable if residents cannot afford the migration costs into safe places or if they fail to follow safety recommendations. Yet the permanence of relocation policies can hardly be expected due to the irreversible investments that have locked people into the location of risk. While choice of residence can in theory be a prominent protective measure against volcanic risk, relocating appears to be associated with substantial sunk costs, great enough to force generations to remain exposed, even once the uncertainty over the risk is resolved and reveals the sub-optimality of the location. Competing with the role of uncertainty about the threat as a reason why people live near volcanoes, the presence of income-generating opportunities that are more profitable than those in safer places also makes volcanic environments attractive. Extracting volcano-related resources (sands and rocks for construction, as well as gems and minerals), offering touristic activities based on volcano landscapes and hot springs, and working in a geothermal power plant would outperform any other employment alternative in a non-volcanic place if wage differentials were large enough to compensate for both the risk involved during the workday and the prospect of business interruption. Similarly, it can be economically optimal not to incur the commuting costs required to live further from the threat.

Ultimately, the efficacy of information campaigns, warnings and evacuation plans is directly dependent on how policymakers and populations communicate and understand and use forecasts that are often highly uncertain. Despite major research literature, finding tools to analyze decision-making under risk where knowledge is known to be incomplete is still an open exercise in economics (see for instance Machina and Siniscalchi (2014), Gilboa and Marinacci (2016) and Al Najjar and Weinstein (2009) on the theoretical literature on ambiguity). Credibly predicting whether and how uncertain information can affect decisions calls for assessing which theory is the most appropriate to describe expectations formation, and revision (Manski, 2004). Empirical evidence reports behaviors departing from Bayes' rule (Poinas et al., 2012; Gallagher, 2014; Baillon et al., 2018). Uncovered "nonstandard" responses that may be observed in volcanic settings include inertia leading to repeat past priors, direct experiences held as more informative than indirect ones (Royal, 2017), and a tendency to decrease protection after the absence of direct losses, regardless of whether the reason was the absence of physical threat or the presence of past mitigation (Meyer, 2012).

5. Macroeconomy of volcanoes

Are natural hazards such as volcanic events a tremendous obstacle to economic growth and development in hazard-prone countries? The question is far from settled. The economic literature focuses on natural events that cause great damage or loss of life, i.e., natural disasters. As the macroeconomic literature on volcanic disasters is virtually non-existent, we refer to natural disasters in general. This section first explores the theoretical mechanisms by which natural disasters, whatever their origin, can affect economic activity. It then examines whether the empirical literature supports the idea that natural disasters in general, and volcanic events in particular, have a powerfully negative effect on economic growth.

5.1. Identifying the channels of transmission

From a theoretical point of view, the effect of a disaster on subsequent economic growth is ambiguous. Growth theories provide three competing hypotheses: first, a slowdown in growth in the short and long term arising from the destruction of capital (the “no recovery hypothesis”); second, an economic boom resulting from the reconstruction effort (the creative destruction and build back better hypothesis); and third, no long-term effect for economies with a greater capacity to absorb shocks (“the recovery to trend hypothesis”).

The traditional neoclassical growth theory teaches us that the immediate loss of the physical capital stock following a natural disaster leads to a drop in output in the short term because the capital per head decreases, as well as the productivity of essential assets such as land. Human capital may also disappear as a result of excess mortality and morbidity, as well as due to potential international population migration. Disruptions in the transport of goods and people and deficiencies in infrastructure and communications are also likely to disturb supply chain management and thus, the production of goods and services. As a result, short-term GDP growth would slow down, and depending on various factors discussed below, the economy could enter a phase of long-term stagnation of per capita output or even never return to pre-disaster levels and trajectory (Hsiang and Jina, 2014; Hochrainer, 2009; Berlemann and Wenzel, 2018).

However, this pessimistic scenario may induce governments to implement countercyclical policies. If public expenditure increases 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 (Albala-Bertrand, 1993). Conversely, if public spending follows a 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 the same vein of argument, if the losses are mainly driven by the uninsured share of the physical capital damaged, a recovery could occur rapidly whenever the insurance coverage is higher (Von Peter and al., 2012; Breckner and al., 2016).

Unlike neoclassical models, endogenous growth models consider that the destruction of productive capital may lead to a “Schumpeterian creative destruction effect” or a “built back better” effect. On the one hand, the destruction of obsolete and unprofitable technologies would have a “cleansing” effect on the productive system and provide an opportunity to adopt new technologies. As a result, a boom in activity would follow the event, with new capital expected to be more efficient than that that was destroyed. On the other hand, increased risk of physical capital destruction may lead to an increase in human capital investment because the latter becomes more attractive. This higher human capital may in turn foster the adoption of new technologies. As a result, the growth rate of total factor productivity should increase (Skidmore and Toya; 2002; Hallegate et Dumas, 2009; Noy and DuPont, 2016).

Whether natural disasters will have significant macroeconomic impact and/or long-lasting effects on growth is still being debated because the breadth and longevity of the effects depend on many key variables. First, the magnitude of the disaster is important. If the share of capital destroyed (both physical and human) is too low compared to the total capital available for production, it cannot weaken the growth of output (Cavallo et al., 2013).

Second, the geographic location of the disaster (urban/rural; coastal/inland) matters because it determines whether the disaster hits a particularly important sector in terms of its contribution to GDP such as agriculture, mining or petroleum activity, which are usual around volcanoes and/or affect densely populated areas. The final effect on economic growth depends on the forward and backward linkages between the sector affected and the rest of the economy. As a result, disasters affect small countries more dramatically than large ones because their economies typically rely on two sectors: 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 (Auffrey, 2003; Coffman and Noy, 2011).

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 a country’s structural characteristics such as its level of development. Natural disasters are expected to have stronger consequences in low-income economies (Fomby et al. 2009; Skidmore and Toya, 2007; Noy, 2009; Raddatz, 2009; Berlemann and Wenzel, 2018). One reason is that agricultural sector, which is highly vulnerable to environmental conditions, figures predominantly in the GDP of these countries. In a more diversified productive structure, powerful endogenous compensation mechanisms can neutralize the negative sectoral impact of a disaster. A second reason is that low-income countries may lack human and material capital, organizational ability, and financial resources to get back to their growth path (Skidmore and Toya, 2007; Crespo and al, 2008).

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 and even contradicting conclusions about the direction and magnitude of the macroeconomic implications of natural disasters. As there are no studies focusing exclusively on volcanic disasters, this section reviews and discusses the literature on the growth impact of natural disasters in general.

Most of the existing literature deals with the short-term effects of disasters on growth and generally shows a negative effect (Felbelmary and Gröshl, 2014; Hochrainer, 2009; Noy and Vu 2010; Raddatz, 2009; Strobl, 2012). As far as long-term effects are concerned, some authors (Cunado and Ferrera 2013; Skidmore and Toya 2002; Leiter and al 2009) find that natural disasters are beneficial and have a positive impact on long-term growth mainly through growth in factor productivity. Other authors find either an insignificant effect (Albala-Bertrand, 1993; Cavallo et al., 2013) of natural disasters on long-term GDP growth or a negative one (Berlemann and Wenzel, 2018).

Different types of natural disasters do have different effects. Few studies specialize in a specific type of disaster, and to the best of our knowledge, none of the studies have focused on volcanic events. However, natural disasters of volcanic origin, which often occur repeatedly in the same areas, may have powerful negative effects on long-term growth. Geological disasters are sometimes isolated in the analysis, but in addition to volcanic eruptions, they include earthquakes, landslides, and tidal waves (Felbelmary and Gröshl, 2014, Raddatz, 2009). The authors find a negative or non-significant effect of geological events on output. To the best of our knowledge, the only study (Felbermayr and Gröschl, 2014), which analyzes the impact of different types of natural disasters on growth, shows that volcanic eruptions are the only events that have no effect on economic growth. This result may arise from their database, which includes 800 volcanic eruptions of which they identify only nine large-scale volcanic disasters[16] over the period studied (1979-2010). Another possible reason is that volcanic events are geographically limited to a region or even a county where the volcano is located and therefore affect a country's economic growth to a lesser extent.

5.3. Future research

The above literature review suggests that natural disasters have complex effects on the economy in which they occur. Therefore, much remains 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 they may affect the different sectors of the economy and the level of development of the affected countries. Whether the impacts will be transitory or permanent is a topic that should also be given more attention. Understanding the interactions between the affected area and the national economy as well as the ability of the affected regions to attract transfers from the central government will also help researchers/economists understand the local effect of a given disaster. Looking at volcanic impact on environmental capital (for example land fertility) and its economic repercussions would be another key point. The reaction of local and national governments on public spending and fiscal policy is yet unknown. Upward pressure on prices in all sectors of the economy (housing, transportation, energy, water, agricultural products, etc.) hit by a volcanic disaster should also be investigated.

6. Discussion

6.1. Challenges relative to socioeconomic data

[16] Events that caused 1,000 or more injured or dead; affected 100,000 or more persons; or caused a monetary damage of 1 billion or more US dollars.

From both the microeconomic and macroeconomic analysis perspectives, the lack of economic research on volcanic hazards and disasters can be explained by the lack of socio-economic data in affected areas, as well by the spatial scale of existing data sets.

Indeed, the availability of socio-economic data on populations affected by volcanic hazards and disasters lags behind the availability of physical information described in Section 2. Economists thus lack sufficient quantitative household level information to provide rigorous analysis around risk management and adaptation policies to volcanic hazards, even more so as volcanic hazards are very localized. On the one hand, the spatial scale of existing household surveys (secondary data) doesn't allow for analysis of 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 at the spatial scale that is needed for conducting economic research on localized volcanic hazards. Indonesia, which is located on the Pacific Ring of Fire and has 142 volcanoes, provides a good illustration of this issue. In a population of 263 million people, over 8.6 million inhabitants live within 10 km from a volcano, over 68 million within 30 km and more than 179 million people within 100 km (Brown et al., 2015) of a volcano. Yet existing large-scale datasets hardly cover these populations. Using four waves of the Indonesian Family Life Survey (IFLS) from 1993-2007, Stéphane (2018) calculated the distances between sampled communities and volcanoes and found that they were located too far away (generally more than 20 km). Furthermore, even if a survey covers clusters close to volcanoes, these clusters contain information for a limited number of households, reducing the potential for rigorous quantitative analysis. Overall, despite the existence of more longitudinal surveys in many affected countries, sample sizes are not sufficient to analyze very localized phenomena such as 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 events have severe impacts on the psychological health of affected populations (Patton et al., 2001; Ruiz et Hernández, 2014). When conducting a field survey in post-disaster areas, it is thus recommended, as suggested by de Jong et al. (2016) and Tansey et al. (2017), that researchers and field teams consider these populations as vulnerable. Recognizing the 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 Jong et al., 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 through working closely and in coordination with local communities and other local stakeholders. Participatory mapping enables the active participation of communities to share their knowledge about volcanic hazards, allowing 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 through prior discussions with community members in order to institutionalize their co-production of data. In the aftermath of a disaster, trained members are more likely to be in a capacity to collect socio-economic data from affected households.

As discussed in previous sections, firms are also affected by volcanic hazards, be they household farms, micro, small & medium enterprises, or larger firms. They can be affected in many ways: through damage or destruction of their inputs, of roads and of other network infrastructure or by lower consumer demand or depletion of their human capital. Yet very little is known empirically about these effects. On the one hand, enterprise surveys, when they exist, have limited sample sizes; on the other hand, just as for household surveys, their spatial scale does not allow for the addressing of research questions about localized volcanic events.

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 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.

The use of satellite images, which is developing fast in economic research, will have obvious advantages in the economics of volcanoes. Nonetheless, satellite images will have limited application as their current resolution doesn't allow us to explore injuries and fatalities, destruction and damage to infrastructure, or any underground damage (e.g., pipes and sewer systems).

In summary, current statistical information provides an insufficient level of details (location of households, gender, age, income groups, etc.) and does not allow researchers to build a pre-volcanic event situation for key socio-economic indicators (baseline scenario). As satellite data initiatives make progress in reporting more physical and socio-economic information, researchers will be able to address more research questions on a topic which has been overlooked.

6.2. Addressing endogeneity

Even with the appropriate socioeconomic data available, empirical challenges remain as to how to identify the effect of volcanic activity on a socio-economic outcome through econometric models. Estimating the causal effect of an independent variable measuring volcanic activity implies dealing with endogeneity (i.e., the regressor correlating with the model's error term) as estimates would otherwise be biased. The previous sections have suggested that such a variable, albeit naturally occurring, can turn out to be endogenous for several reasons.

We can assume that the main reason would be that since volcanic hazards are driven by stochastic geophysical processes, then no confounding factor could correlate with both the independent variable and a socio-economic dependent variable. Instead, volcanic locations are associated with geographic features and other geophysical hazards (see Subsection 2.1) able to affect the economic system on their own. Subsection 2.2 emphasized that the quality of self-reported volcanic disaster counts, and losses depends on economic and political considerations that may confound results. In the same vein, the different methodologies applied when assessing volcanic disaster costs (see Section 3) can lead to a measurement error that may be systematically influenced by certain characteristics of the countries as well. According to Section 4, whether a household is exposed to volcanic hazard is suspected to be linked with pre-existing differences, since individuals can self-select through migration. Another issue raised by Subsection 6.1 relates to the unrepresentativeness of samples and incompleteness of datasets supposed to reflect what a population affected by a volcanic disaster “is like” in its aftermath. Omitted variables and an unmodeled selection process would therefore cast doubt on results.

Strategies applied in the natural disaster literature to overcome some of these issues include the use of rich panel datasets to control for time-invariant confounders (e.g., Boustan et al., 2018), impact evaluation techniques to build a more appropriate counterfactual (e.g., Coffman and Noy, 2012; Deryugina et al., 2018), physical measures of the hazard as independent variable (e.g., Hsiang and Jina, 2014) and instrumental variables (e.g., Noy and Vu, 2010). In a study specifically focused on volcanic-aerosol hazard, a noteworthy approach applied by Halliday et al. (2019) consists in using data on wind direction as an instrument for the hazard.

If these strategies can provide convincing disaster impact estimates, questions on the long-term consequences of inherent volcanic activity risk - including risk in the absence of recent hazardous events – still require a more causal framework. As suggested in Sections 4 and 5, because locations where eruption struck in the past are also those with higher exposure to future volcanic events, the permanence of the effects of past events, combined with all potential confounders and ex-ante adaptation behaviors, could make volcanic location paths so singular that no non-volcanic location would yield an appropriate counterfactual. Volcanic islands are an illustration of this unique setting. Yet without exogenous changes in a similar location’s volcanic risk (e.g., the outbreak of a new volcano) that could serve as a natural experiment, studies of the exposure to volcanic risk would have to rely on cross-sectional approaches using observed data on non-volcanic locations as the counterfactual.

To tackle this issue of “missing data” on the path of volcanic locations in the absence of volcanic risk, simulation methods can be useful tools. Indeed, input-output models and computable general equilibrium models aren’t yet popular in disaster assessment research (Rose, 2004; Galbusera and Giannopoulos, 2018). Their application can extend to ex-ante evaluations of the worthiness of risk mitigation measures, a question that is extremely difficult to address though econometric models. Stéphane (2018) provides a rare simulation exercise based on a model describing farm asset accumulation that identifies ex-ante effects of volcanic risk and effects due to changes in risk perception as the result of past eruptions. Simulation methods may also be able to overcome some of the challenges relative to socio-economic data, and compliment econometric models when studying volcanoes in economics, in particular whenever endogeneity cannot be convincingly addressed.

7. Concluding remarks

Despite the extensive damage caused by volcanic eruptions, there are relatively few studies, both at the micro and macroeconomic levels, which focus on the economic impacts of volcanoes. This paper presents a review of our current state of knowledge of volcanic impacts, raises some methodological challenges and highlights a number of research needs.

Many LMICs are exposed to volcanic hazards and, for many reasons, are particularly vulnerable to the impacts of these hazards. The exposed populations are usually poor and uninsured against volcanic risk. Expecting households to resettle away from dangerous zones is unrealistic because livelihoods are not easily transferable from one economic sector to another or from one locality to another and moving is costly. One of the principal policy challenges is thus to implement efficient public policies aimed at supporting adaptation and resilience of people living under the threat of volcanoes.

8. References

Al Najjar, N. I., & Weinstein, J. (2009). The ambiguity aversion literature: A critical assessment. *Economics and Philosophy, 25*, 249–284. doi:10.1017/S026626710999023X

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., & Hsiang, S. (2013). *Destruction, disinvestment, and death: Economic and human losses following environmental disaster.* Goldman School of Public Policy Working Paper. doi:10.2139/ssrn.2220501

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

Baillon, A., Bleichrodt, H., Keskin, U., Olivier, & Li, C. (2018). The Effect of Learning on Ambiguity Attitudes. *Management Science, 64*, 2181-2198. doi:10.1287/mnsc.2016.2700

Barclay, J., Few, R., Armijos, M. T., Phillips, J. C., Pyle, D. M., Hicks, A., Brown, S.K. & Robertson, R. E. (2019). Livelihoods, Wellbeing and the Risk to Life During Volcanic Eruptions. *Frontiers in Earth Science, 7*. doi:10.3389/feart.2019.00205

Berlemann, M., & Wenzel, D. (2018). Hurricanes, economic growth and transmission channels. *World Development, 105*, 231-247. doi:10.1016/j.worlddev.2017.12.020

Blumenstock, J. E., Eagle, N., & Fafchamps, M. (2016). Airtime transfers and mobile communications: Evidence in the aftermath of natural disasters. *Journal of Development Economics, 120*, 157-181. doi:10.1016/j.jdeveco.2016.01.003

Bohra Mishra, P., Oppenheimer, M., & Hsiang, S. M. (2014). Nonlinear permanent migration response to climatic variations but minimal response to disasters. *Proceedings of the National Academy of Sciences, 111*, 9780-9785. doi:10.1073/pnas.1317166111

Boustan, L., Kahn, M., Rhode, P., & Yanguas, M. L. (2018). *The Effect of Natural Disasters on Economic Activity in US Counties: A Century of Data.* UCLA California Center for Population Research. Available online at: http://papers.ccpr.ucla.edu/index.php/pwp/article/view/1221 (accessed 05 July 2019)

Breckner, M., Englmaier, F., Stowasser, T., & Sunde, U. (2016). Resilience to natural disasters — Insurance penetration, institutions, and disaster types. *Economics Letters, 148*, 106-110. doi:10.1016/j.econlet.2016.09.023

Brown, S. K., Loughlin, S. C., Sparks, R. S., & Vye-Brown, C. (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 Earth's Interior*.

Browne, M. J., & Hoyt, R. E. (2000). The Demand for Flood Insurance: Empirical Evidence. *Journal of Risk and Uncertainty, 20*, 291-306. doi:10.1023/A:1007823631497

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. doi:10.1016/j.jdeveco.2017.03.007

Cavallo, E., & Noy, I. (2011). Natural disasters and the economy—a survey. *International Review of Environmental and Resource Economics, 5*, 63-102.

Cavallo, E., Galiani, S., Noy, I., & Pantano, J. (2013). Catastrophic Natural Disasters and Economic Growth. *Review of Economics and Statistics, 95*, 1549-1561. doi:10.1162/REST_a_00413

Champ, P. A., Boyle, K. J. & Brown, T. C. (Eds.). (2003). *A primer on nonmarket valuation* (Vol. 3). Springer. doi:10.1007/978-94-007-0826-6

Choumert Nkolo, J., & Phélinas, P. (2020). Natural disasters, land and labour. *European Review of Agricultural Economics*. 47, 296-323. doi:10.1093/erae/jbz030

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

CRED. (2019). *Volcanic Activity and Wildfires.* CRED Crunch, Centre for Research on the Epidemiology of Disaster. Available online at: https://reliefweb.int/sites/reliefweb.int/files/resources/CRED CRUNCH55.pdf (accessed 04 December 2019)

Crespo Cuaresma, J., Hlouskova, J., & Obersteiner, M. (2008). Natural disasters as creative destruction? Evidence from developing countries. *Economic Inquiry, 46*, 214-226.

Cunado, J., & Ferreira, S. (2014). The macroeconomic impacts of natural disasters: the case of floods. *Land Economics, 90*, 149-168.

De Groeve, T., Poljansek, K., & Ehrlich, D. (2013). *Recording Disaster Losses: Recommendations for a European approach.* European Commission Joint Research Centre. doi:10.2788/98653

Dercon, S. (2004). Growth and shocks: evidence from rural Ethiopia. *Journal of Development Economics, 74*, 309-329. doi:10.1016/j.jdeveco.2004.01.001

Deryugina, T., Heutel, G., Miller, N. H., Molitor, D., & Reif, J. (2019). The Mortality and Medical Costs of Air Pollution: Evidence from Changes in Wind Direction. *American Economic Review, 109*, 4178-4219. doi:10.1257/aer.20180279

Deryugina, T., Kawano, L., & Levitt, S. (2018). The Economic Impact of Hurricane Katrina on Its Victims: Evidence from Individual Tax Returns. *American Economic Journal: Applied Economics, 10*, 202-33. doi:10.1257/app.20160307

Doucouliagos, C., Stanley, T. D., & Giles, M. (2012). Are estimates of the value of a statistical life exaggerated? *Journal of Health Economics, 31*, 197-206. doi:10.1016/j.jhealeco.2011.10.001

Elbers, C., Gunning, J. W., & Kinsey, B. (2007). Growth and Risk: Methodology and Micro Evidence. *World Bank Economic Review, 21*, 1-19. doi:10.1093/wber/lhl008

Ewert, J. W., & Harpel, C. J. (2004). In harm's 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.

Fafchamps, M. (1993). Sequential Labor Decisions Under Uncertainty: An Estimable Household Model of West-African Farmers. *Econometrica, 61*, 1173-1197.

Fafchamps, M., & Gubert, F. (2007). The formation of risk sharing networks. *Journal of Development Economics, 83*, 326-350. doi:10.1016/j.jdeveco.2006.05.005

Faurie, C., Mettling, C., Bchir, M. A., Hadmoko, D. S., Heitz, C., Lestari, E. D., Raymond, M. & Willinger, M. (2016). Evidence of genotypic adaptation to the exposure to volcanic risk at the dopamine receptor DRD4 locus. *Scientific reports, 6*, 37745. doi:10.1038/srep37745

Fearnley, C. J., Bird, D. K., Haynes, K., McGuire, W. J., & Jolly, G. (Eds.). (2018). *Observing the Volcano World. Volcano Crisis Communication.* (773 p.). Springer-Verlag GmbH.

Felbermayr, G., & Gröschl, J. (2014). Naturally negative: The growth effects of natural disasters. *Journal of development economics, 111*, 92-106.

Fomby, T., Ikeda, Y., & Loayza, N. V. (2009). The growth aftermath of natural disasters. *Journal of Applied Econometrics, 28*, 412-434. doi:10.1002/jae.1273

Freire, S., Florczyk, A., Pesaresi, M., & Sliuzas, R. (2019). An Improved Global Analysis of Population Distribution in Proximity to Active Volcanoes, 1975–2015. *ISPRS International Journal of Geo-Information, 8*, 341. doi:10.3390/ijgi8080341

Gaddis, E. B., Miles, B., Morse, S., & Lewis, D. (2007). Full-cost accounting of coastal disasters in the United States: Implications for planning and preparedness. *Ecological Economics, 63*, 307-318. doi:10.1016/j.ecolecon.2007.01.015

Gaillard, J. C., Cadag, J. R., Gampell, A., Hore, K., Le Dé, L., & McSherry, A. (2016). Participatory numbers for integrating knowledge and actions in development. *Development in Practice, 26*, 998-1012.

Galbusera, L., & Giannopoulos, G. (2018). On input-output economic models in disaster impact assessment. *International Journal of Disaster Risk Reduction, 30*, 186-198. doi:10.1016/j.ijdrr.2018.04.030

Gallagher, J. (2014). Learning about an Infrequent Event: Evidence from Flood Insurance Take-Up in the United States. *American Economic Journal: Applied Economics, 6*, 206-233.

Gilboa, I., & Marinacci, M. (2016). Readings in formal epistemology. In: H. Arló-Costa, V. F. Hendricks, J. Benthem, H. Arló-Costa, V. F. Hendricks, & J. Benthem (Eds.), *Readings in Formal Epistemology: Sourcebook* (pp. 385-439). Cham: Springer International Publishing. doi:10.1007/978-3-319-20451-2_21

Gill, J. C., & Malamud, B. D. (2014). Reviewing and visualizing the interactions of natural hazards. *Reviews of Geophysics, 52*, 680-722.

Global Volcanic Program. (2013). Volcanoes of the World, v. 4.8.6 (20 Feb 2020). Venzke, E (ed.). Smithsonian Institution. doi.org/10.5479/si.GVP.VOTW4-2013 National Geophysical Data Center / World Data Service (NGDC/WDS). NCEI/WDS Global Significant Volcanic Eruptions Database. NOAA National

Gollier, C., & Pratt, J. W. (1996). Risk Vulnerability and the Tempering Effect of Background Risk. *Econometrica, 64*, 1109-1123.

Graff Zivin, J., & Neidell, M. (2012). The Impact of Pollution on Worker Productivity. *American Economic Review, 102*, 3652-3673. doi:10.1257/aer.102.7.3652

Gröger, A., & Zylberberg, Y. (2016). Internal Labor Migration as a Shock Coping Strategy: Evidence from a Typhoon. *American Economic Journal: Applied Economics, 8*, 123-53. doi:10.1257/app.20140362

GVP. (2020) Current Eruptions. Available online at: http://volcano.si.edu/gvp_currenteruptions.cfm (accessed 24 February 2020)

Halkos, G., & Zisiadou, A. (2019). Examining the Natural Environmental Hazards Over the Last Century. *Economics of Disasters and Climate Change*, *3*(2), 119-150.

Hallegatte, S., & Dumas, P. (2009). Can natural disasters have positive consequences? Investigating the role of embodied technical change. *Ecological Economics, 68*, 777-786.

Hallegatte, S., & Przyluski, V. (2010). *The economics of natural disasters: concepts and methods.* Policy Research Working Paper. The World Bank.

Halliday, T. J., Lynham, J., & De Paula, Á. (2019). Vog: Using Volcanic Eruptions to Estimate the Health Costs of Particulates. *Economic Journal, 129*, 1782-1816. doi:10.1111/ecoj.12609

Hansell, A. L., Horwell, C. J., & Oppenheimer, C. (2006). The health hazards of volcanoes and geothermal areas. *Occupational and environmental medicine, 63*, 149-125. doi:doi:10.1136/oem.2005.022459

Hearne, R. R., & Salinas, Z. M. (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?* Policy Research Working Paper. 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. doi:10.1257/aer.102.4.1477

Hsiang, S. M., & Jina, A. S. (2014). *The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones.* NBER Working Papers, National Bureau of Economic Research. Available online at: https://ideas.repec.org/p/nbr/nberwo/20352.html (accessed 06 July 2019)

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

Jackson, E., & Aboagye, D. (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)

Jong, J., Hibben, K. C., & Pennell, S. (2016). *Ethical Considerations. Guidelines for Best Practice in Cross-Cultural Surveys.* Ann Arbor, MI: Survey Research Center, Institute for Social Research, University of Michigan.

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

Kocornik Mina, A., McDermott, T. K., Michaels, G., & Rauch, F. (2015). *Flooded cities.* GRI Working Papers, Grantham Research Institute on Climate Change and the Environment. Available online at: https://ideas.repec.org/p/lsg/lsgwps/wp221.html (accessed 04 December 2019)

Lansing, J. S., Kremer, J. N., Gerhart, V., Kremer, P., Arthawiguna, A., Surata, S. K., Suprapto, Suryawan, I. B., Arsana, I. G., Scarborough, V. L., Schoenfelder, J., & Mikita, K. (2001). Volcanic fertilization of Balinese rice paddies. *Ecological Economics, 38*, 383-390. doi:10.1016/S0921-8009(01)00173-2

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

Ligon, E., & Schechter, L. (2003). Measuring Vulnerability. *Economic Journal, 113*, C95-C102. doi:10.1111/1468-0297.00117

Maccini, S., & Yang, D. (2009). Under the Weather: Health, Schooling, and Economic Consequences of Early-Life Rainfall. *American Economic Review, 99*, 1006-26. doi:10.1257/aer.99.3.1006

Machina, M. J., & Siniscalchi, M. (2014). Chapter 13 - Ambiguity and Ambiguity Aversion. In: M. Machina, & K. Viscusi (Eds.), *Handbook of the Economics of Risk and Uncertainty* (Vol. 1, pp. 729-807). North-Holland. doi:10.1016/B978-0-444-53685-3.00013-1

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

Manski, C. F. (2004). Measuring Expectations. *Econometrica, 72*, 1329-1376. doi:10.1111/j.1468-0262.2004.00537.x

Martí, J., & Ernst, G. G. (Eds.). (2009). *Volcanoes and the Environment.* Cambridge University Press. doi:10.1017/CBO9780511614767

Melecky, M., & Raddatz, C. (2014). Fiscal responses after catastrophes and the enabling role of financial development. *The World Bank Economic Review, 29*, 129-149.

Meyer, R. J. (2012). Failing to learn from experience about catastrophes: The case of hurricane preparedness. *Journal of Risk and Uncertainty, 45*, 25-50. doi:10.1007/s11166-012-9146-4

Musafili, I., Ngabitsinze, J. C., Niyitanga, F., & Weatherspoon, D. (2019). Farmers' usage preferences for Rwanda's Volcanoes National Park. *Journal of Agribusiness in Developing and Emerging Economies, 9*, 63-77. doi:10.1108/JADEE-01-2018-0004

Newhall, C. G., & Self, S. (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. doi:10.1016/j.jdeveco.2008.02.005

Noy, I., & Vu, T. B. (2010). The economics of natural disasters in a developing country: The case of Vietnam. *Journal of Asian Economics, 21*, 345-354.

Noy, I., & duPont IV, W. (2016). *The long-term consequences of natural disasters - A summary of the literature.* Working Paper Series, Victoria University of Wellington, School of Economics and Finance. Available online at: https://EconPapers.repec.org/RePEc:vuw:vuwecf:4981 (accessed 04 March 2020)

Paton, D., Millar, M., & Johnston, D. (2001). Community resilience to volcanic hazard consequences. *Natural hazards, 24*, 157-169.

Poinas, F., Rosaz, J., & Roussillon, B. (2012). Updating beliefs with imperfect signals: Experimental evidence. *Journal of Risk and Uncertainty, 44*, 219-241. doi:10.1007/s11166-012-9143-7

Raddatz, C. (2009). *The wrath of God: macroeconomic costs of natural disasters.* Policy Research Working Paper. 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., Schwarze, R., Schwindt, M., & Zahn, F. (2013). Uncertainty of Governmental Relief and the Crowding out of Flood Insurance. *Environmental and Resource Economics, 54*, 179-200. doi:10.1007/s10640-012-9586-y

Rose, A. (2004). Economic principles, issues, and research priorities in hazard loss estimation. In: Okuyama Y., Chang S.E. (Eds.), *Modeling spatial and economic impacts of disasters. Advances in Spatial Science* (pp. 13-36). Springer.

Rosenzweig, M. R., & Binswanger, H. P. (1993). Wealth, Weather Risk and the Composition and Profitability of Agricultural Investments. *The Economic Journal, 103*, 56-78.

Rosenzweig, M. R., & Stark, O. (1989). Consumption Smoothing, Migration, and Marriage: Evidence from Rural India. *Journal of Political Economy, 97*, 905-926. doi:10.1086/261633

Rosenzweig, M. R., & Wolpin, K. I. (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.

Royal, A. (2017). Dynamics in risk taking with a low-probability hazard. *Journal of Risk and Uncertainty, 55*, 41-69. doi:10.1007/s11166-017-9263-1

Ruiz, C., & Hernández, B. (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., & Takasaki, Y. (2017). Natural Disaster, Poverty, and Development: An Introduction. *World Development, 94*, 2-15. doi:10.1016/j.worlddev.2016.12.035

Schwefer, M. (2018). *Sitting on a Volcano: Domestic Violence in Indonesia Following Two Volcano Eruptions.* Ifo Working Paper Series, Ifo Institute - Leibniz Institute for Economic Research at the University of Munich. Available online at: https://ideas.repec.org/p/ces/ifowps/_263.html (accessed 06 July 2019)

Sigmundsson, F., Hreinsdóttir, S., Hooper, A., Árnadóttir, T., Pedersen, R., Roberts, M. J., Oskarsson, N., Auriac, A., Decriem, J., Einarsson, P., Geirsson, H., Hensch M., Ofeigsson, B. G., Sturkell, E., Sveinbjörnsson, H. & Feigl, K. L. (2010). Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption. *Nature, 468*, 426.

Simkin, T., & Siebert, L. (1984). Explosive eruptions in space and time: durations, intervals, and a comparison of the world's active volcanic belts. In: National research Council, *Explosive Volcanism: Inception, Evolution, and Hazards* (pp. 110-121). The National Academic Press. https://doi.org/10.17226/18602

Simkin, T., & Siebert, L. (1994). Volcanoes of the World 2nd Edition. *Geosciences Press (349 p.).*

Simkin, T., Siebert, L., & Blong, R. (2001). Volcano fatalities--lessons from the historical record. *Science, 291*, 255. doi:10.1126/science.291.5502.255

Skidmore, M., & Toya, H. (2002). Do natural disasters promote long-run growth? *Economic inquiry, 40*, 664-687.

Small, C., & Naumann, T. (2001). The global distribution of human population and recent volcanism. *Environmental Hazards, 3*, 93-109. doi:10.1016/S1464-2867(02)00002-5

Stark, O., & Lucas, R. E. (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.* Ph.D. 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., Ribière, C., Scarth, A., & Tjetjep, W. S. (1998). Victims from volcanic eruptions: a revised database. *Bulletin of volcanology, 60*, 137-144.

Tansey, C. M., Anderson, J., Boulanger, R. F., Eckenwiler, L., Pringle, J., Schwartz, L., & Hunt, M. (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.

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. doi:10.2307/2297901

Von Peter, G., Von Dahlen, S., & Saxena, S. C. (2012). *Unmitigated disasters? New evidence on the macroeconomic cost of natural catastrophes.* BIS Working Paper. Bank for International Settlements.

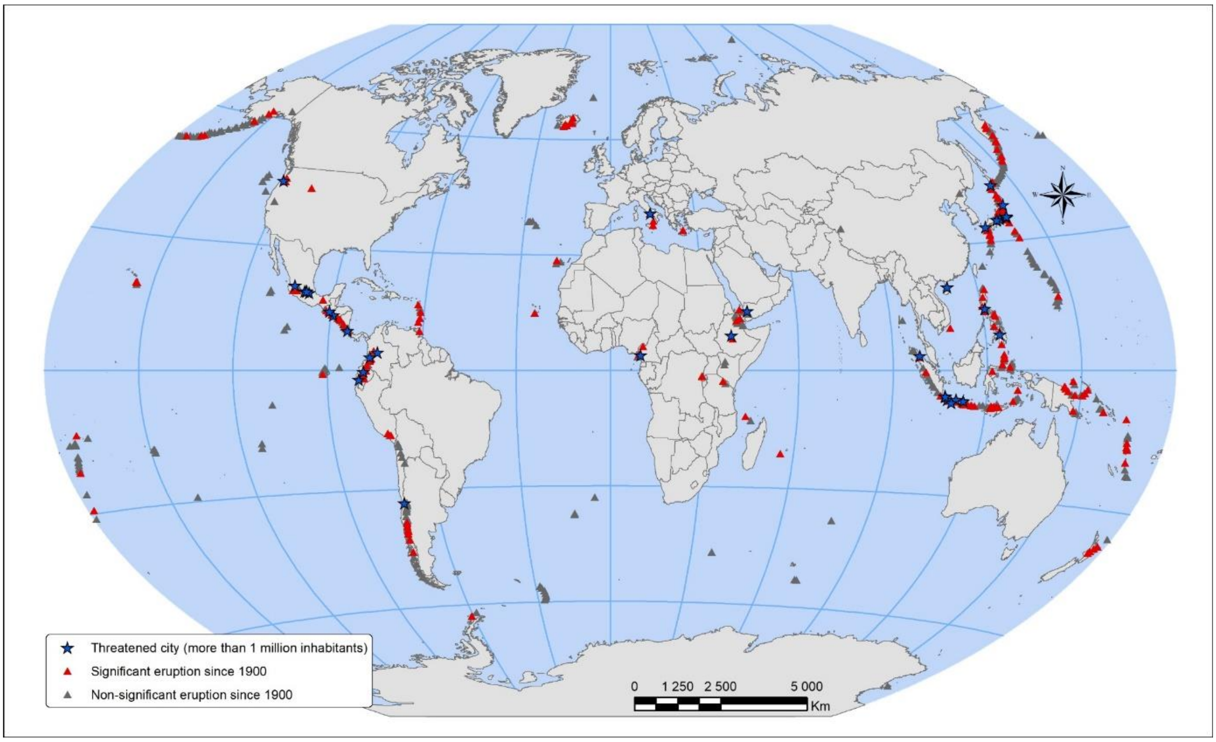
WB/ECLAC/PNUD. (2018). *Evaluación de daños y pérdidas del Volcán de Fuego.* Technical report. The World Bank.

Witham, C. S. (2005). Volcanic disasters and incidents: A new database. *Journal of Volcanology and Geothermal Research, 148*, 191-233.

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

Appendix A. Global distribution of volcanoes

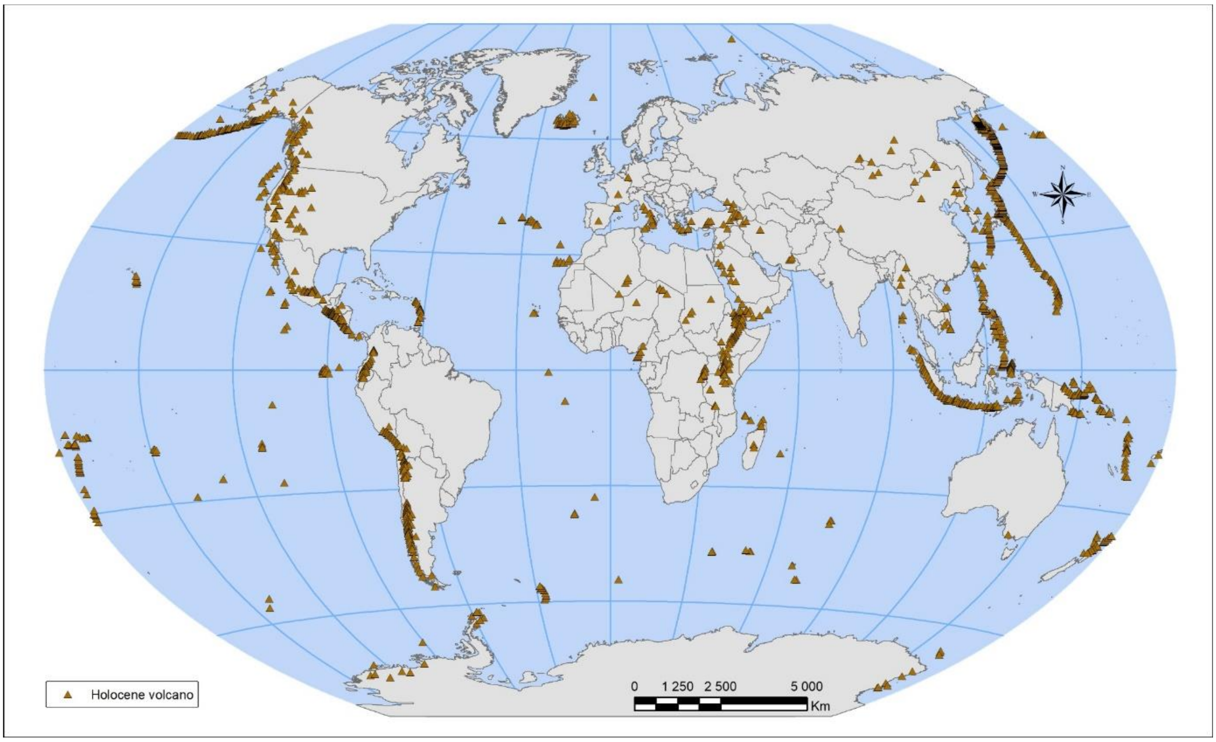
Map 1. Eruptions since 1900



Source: Olivier Santoni (CERDI) using data from the Global Volcanic Program (2013)

Note: Volcanic eruptions that occurred since 1900 and cities of more than 1 million inhabitants located at less than 100 km of a volcano that erupted at least once since 1900. Significant eruptions are eruptions that meet at least one of the following criteria: caused fatalities, caused $1 million damage or more, VEI of 6 or more, caused a tsunami, or was associated with a major earthquake (source: NGDC/WDS). Non-significant eruptions are eruptions that do not meet any of the aforementioned criteria (source: Global Volcanic Program).

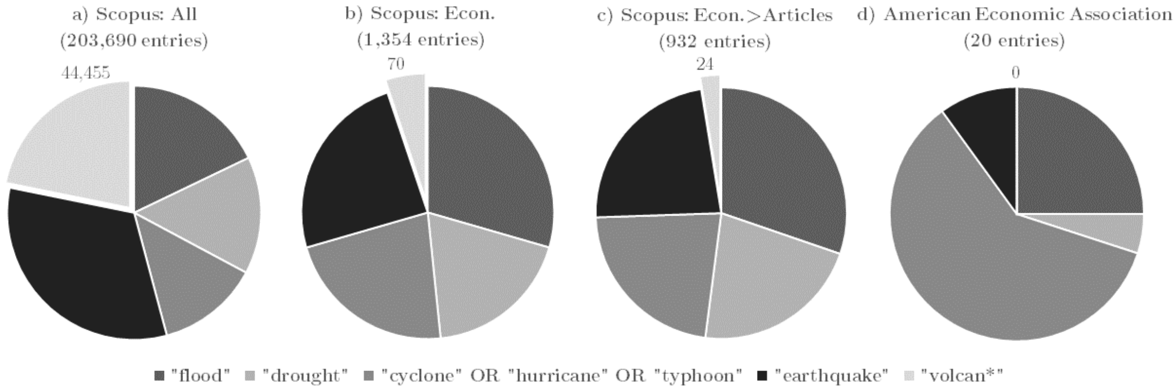
Map 2. Holocene volcanoes



Source: Olivier Santoni (CERDI) using data from the Global Volcanic Program (2013)

Note: Volcanoes with eruptions during the Holocene period (approximately the last 10,000 years) (source: Global Volcanic Program).

Appendix B. The economics of volcanoes?



Number of bibliographic database entries mentioning at least one type of natural hazard in its title a) among all Scopus entries, all subject areas and document types included; b) among Scopus entries with “economics”, “econometrics “or “finance” as a subject area of the source, all document types included; c) among Scopus entries that are articles published in a peer-reviewed or trade journal with “economics”, “econometrics” and “finance”as a subject area of the journal; d) among all entries of the American Economic Association. The use of a wildcard character in “volcan*” means that the search found “volcano”, “volcanic”, and “volcanism”. Data extracted on 04 December 2019.