Dynamic and Extensive Risk Arising from Volcanic Ash Impacts on Agriculture

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Summary

Volcanic Ash is an excellent archetype of an 'extensive hazard'. Ash fall occurs frequently and intermittently during volcanic eruptions, and populations in close proximity to persistently-active volcanoes report ash impacts and distribution that have complex spatial patterns. This is reflected in high-resolution modelling of ash dispersion that integrates local atmospheric and topographic effects. We review three case study long-lasting eruptions in the Caribbean and Ecuador, to highlight the extensive characteristics of ash eruption, deposition, and impacts. Over the long term, attritional effects of volcanic ash create negative impacts on livelihood trajectories via loss of income and nutrition from agriculture, and damage to, and increased maintenance of, critical infrastructure. There are also benefits; communities report that over short time periods following eruptions, there is often increased agricultural productivity. Recognition of the extensive nature of volcanic ash impacts has direct implications for disaster risk reduction policy and practice. These include the need to: anticipate long-lasting costs of relief and potentially severe impacts on people's wellbeing; plan flexibly to respond to high spatial and temporal variability in impacts; and to be cognisant of communities' adaptations and actions to maintain livelihoods when undertaking external interventions. Our work highlights that collaborations between populations at risk, scientists and managers of risk can create pragmatic solutions that mitigate the most serious impacts and exploit the benefits of volcanic ash.

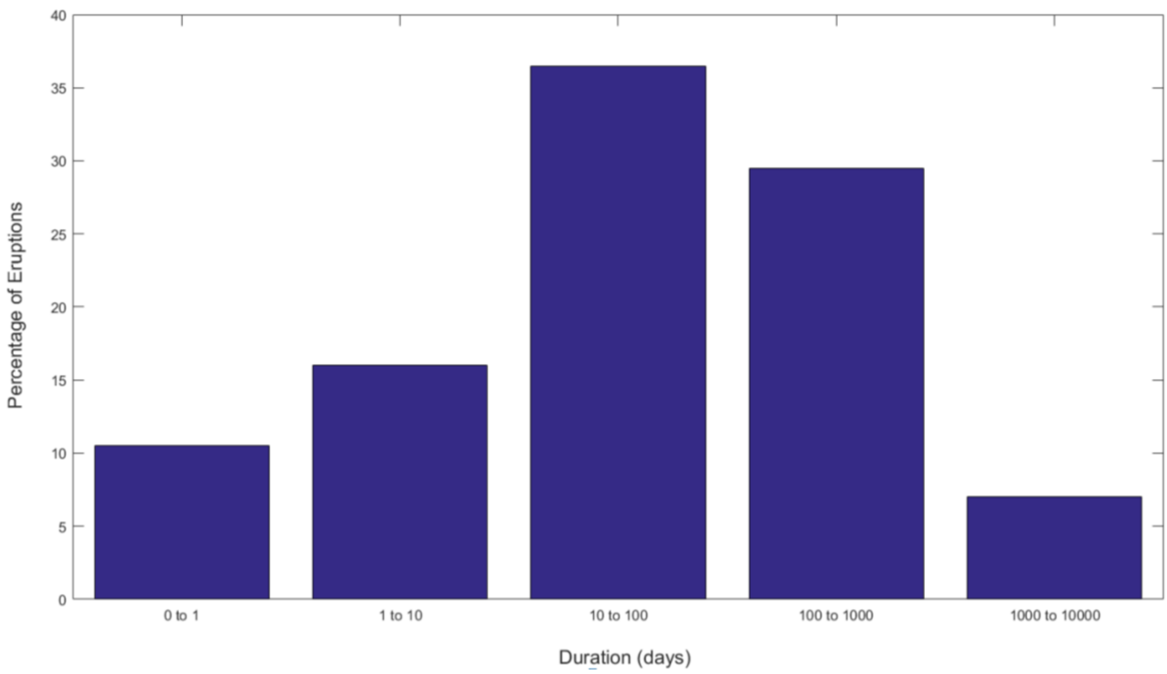
1. Introduction

"Extensive risk is used to describe the risk associated with low-severity, high-frequency events, mainly but not exclusively associated with highly localized hazards. Intensive risk is used to describe the risk associated to high-severity, mid to low-frequency events, mainly associated with major hazards." (UNISDR Global Assessment Report 2015)

For natural hazards including floods, landslides and volcanic eruptions, more frequent events are typically smaller and of lower severity (e.g. Hergarten, 2004). Frequently occurring natural hazards thus pose an extensive risk that is comparable to that which individuals or communities face from other forms of threat including poverty, health risks, or crime (e.g. Reyes-Pando and Lavell, 2012), and that have significant, sustained and cumulative impact on livelihoods and wellbeing across populations (Guppy and Twigg 2013, UNISDR 2015). Extensive hazard events primarily threaten livelihood, rather than life, and affected communities can develop purposeful adaptations to mitigate their impacts, in the same way that they do for other 'everyday' threats. In this way, extensive risk can be viewed as a continuous risk *process* with on-going social impacts for the vulnerable, reproduced by relatively minor but recurrent hazard events (Few, et al, 2017). A critical challenge for understanding disaster risk is improved knowledge and understanding of how people respond to extensive or 'everyday' risks (Dodman et al., 2013), and how this interacts with external interventions in disaster risk management (Reyes-Pando and Lavell, 2012). In this paper, we present new evidence from analysis of eruption records, high resolution modelling and longitudinal interdisciplinary studies of volcanic eruptions that shows how the impacts of volcanic eruptions are both extensive and dynamic. This view broadens knowledge of volcanic ash impacts beyond existing studies (Jenkins, et al, 2015; UNISDR 2015) that focus on how physical impacts vary with distance from source, without considering the social context of poverty, access to resources and capabilities. Understanding the characteristics of natural hazards is critical for planning external interventions to mitigate their consequences, and is foundational for the goal of building the resilience of the poor and agricultural communities to environmental shocks and disasters, underpinning UN Sustainable Development Goals (SDG) 1, 2 and 11.

Most hazards from volcanic eruptions are extensive: activity may persist over long durations (weeks to years); hazardous emissions often recur and change dynamically during eruptions; and impacts are felt over the timescales of livelihood maintenance. While the largest eruptions that can often be characterised as a single high-severity explosive event have typically attracted the most attention, these events are rare and not typical of ongoing global volcanic activity. A global compilation of eruption records shows clearly the extensive nature of volcanic activity (Figure 1) – the median duration of a volcanic eruption is seven weeks, and while explosive episodes (paroxysms) occur most frequently at the start of an eruption, they recur over the eruption duration. Over these timescales, repeated impacts may stress risk management systems through repeated or prolonged evacuations. They also disrupt actions to maintain or recover livelihoods, particularly those based on agriculture, often placing a disproportionate burden on lower-income households (Choumert and Phelinas, 2018). Over the multi-year timescales of longer eruptions, economic growth is inhibited and development is undermined, but, critically, communities can adapt to mitigate the effects of eruption impacts, and environmental benefits including increased soil fertility can emerge.

Figure 1 Duration of volcanic eruptions (median is approximately 7 weeks), after Siebert, et al (2015)



Explosive activity during volcanic eruptions is characterised by the emission of volcanic particles. Strictly, 'volcanic ash' is a term given to particles with diameters less than 2 mm (e.g. Cashman and Rust, 2017), but the term is used more generally for explosive volcanic products of all sizes when communicating volcanic impacts, and with communities and stakeholders, and we adopt this use here. Explosive activity is categorised by typology based on observed large-scale behaviour (e.g. Siebert, et al, 2015). *Strombolian* eruptions produce discrete (seconds duration) and periodic explosions that eject magma fragments in ballistic trajectories which deposit close to the volcano. *Vulcanian* eruptions are more powerful, short-duration (minutes duration), periodic eruptions which produce volcanic plumes transporting ash to tropospheric levels where it is dispersed by the wind. *Plinian* eruptions are sustained (hours duration) explosive eruptions that produce plumes and ash clouds up to stratospheric levels and ash dispersion over 100s to 1000s km range; *Sub-Plinian* eruptions are a subdivision of smaller Plinian eruptions characterised by the size distribution of the ejected particles. Hazards from explosive eruptions also include destructive hot volcanic avalanches called pyroclastic density currents (PDC) that result from gravitational collapse of growing lava domes or partial collapse of volcanic plumes. Ash deposited through this activity can be remobilised by rainfall as lahars (destructive volcanic mudflows) and by the wind as resuspended ash fall. These hazards may persist for months to years during an eruption, and for many years following eruptions.

Figure 2 Volcanic ash eruptions of different scale: top left - Strombolian eruption of Santiaguito, Guatemala (Matthew Watson), top right – Vulcanian eruption of Tungurahua, Ecuador (Maria Teresa Armijos), bottom – Plinian eruption of Calbuco, Chile (Aeveraal [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)])

Long-lasting eruptions typically show distinct phases of different types of explosive activity. The eruption of Soufrière Hills Volcano, Montserrat (1995-present) has so far produced five phases of lava dome growth accompanied by PDC and episodes ranging from sub-Plinian to Vulcanian eruptions producing ash fall (Wadge, et al, 2014). The eruption of Volcán Tungurahua (1999-2016) evolved through distinctive phases of Strombolian activity into Vulcanian activity as the depth of the magma source changed, producing PDC and ashfall throughout the eruption (Mothes, et al, 2015). Fuego Volcano in Guatemala produced a fatal paroxysmal eruption in June 2018; this was preceded by 16 years of near-continuous Strombolian and Vulcanian eruptions every few days producing ash fall within 20 km of the volcano and small PDC (Waite, et al, 2013). Even volcanoes that produce cataclysmic eruptions, such as Mt St Helens (USA), also show repeated episodic activity, in this case, small ash fall events from 1980-86 and 2004-08 (Dzurisin, et al, 2013).

Recognition that volcanic activity is long-lasting and spatially variable is reflected in recent studies of human vulnerability focussing on wellbeing and livelihoods, and the long-term positive and negative consequences of volcanic activity (Bachri, et al, 2015; Dove, 2008; Gaillard, 2008; Hicks and Few, 2015; Kelman and Mather, 2008; Paton, et al, 2001; Thorvaldsdóttir and Sigbjörnsson, 2015; Few, et al, 2017). In this paper, we present results from longitudinal multidisciplinary studies that build from this basis and which highlight the interrelation of extensive hazards and social vulnerability in shaping volcanic risk (Hicks and Few, 2015; Armijos, et al, 2017; Few, et al, 2017). To simplify and draw out key lessons learned, we focus on explosive eruptions, and on one product of those, volcanic ash dispersed in the atmosphere. We further focus on ash impacts on agricultural communities, not only because this is a relatively neglected sector, but also because of the potential damage caused to the rural livelihoods and food security of the poor over wide areas in the developing world (SDG 2). The long-term view taken has allowed us to identify purposeful adaptations to both agricultural production and risk management systems that need to be recognised in external interventions to manage extensive risk and support livelihood maintenance. This paper therefore brings together evidence for the temporally and spatially extensive nature of volcanic ash hazard, its impacts on agricultural communities and their adaptations, and effective risk management strategies that recognise this extensive character. In doing so, it contributes to the GAR core objective of understanding environmental shocks and disasters, through analysis of social and environmental impacts and risk management systems for environmental hazards and risks.

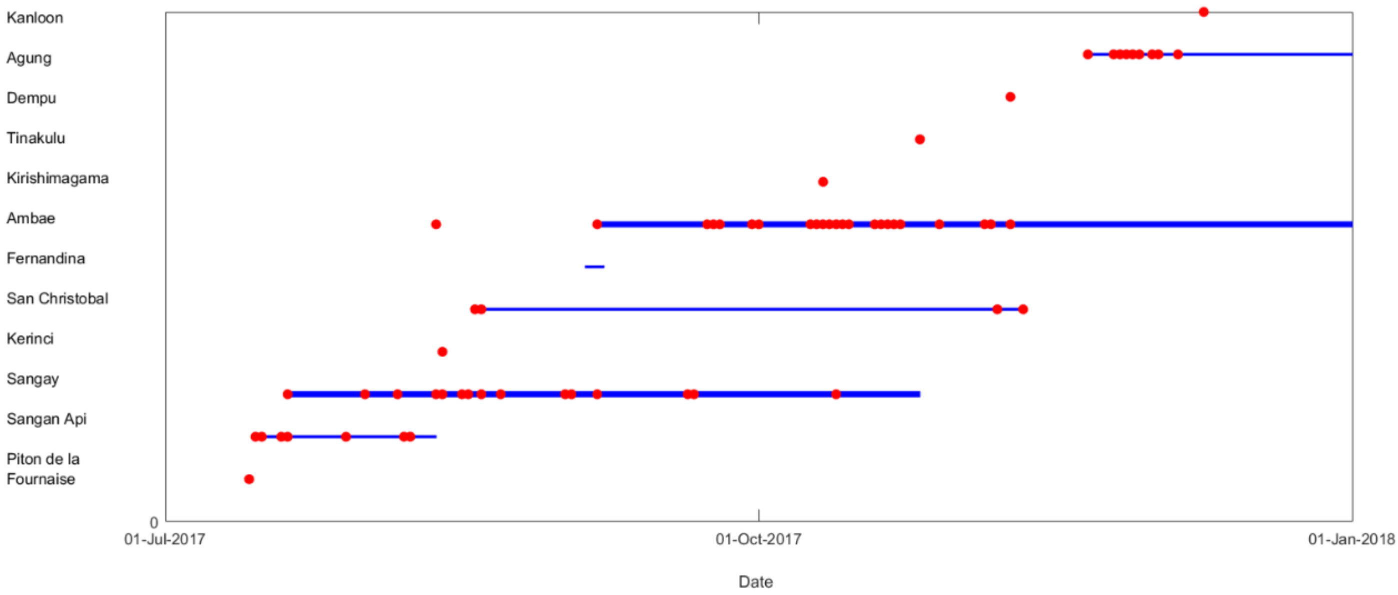
2. Temporal and Spatial Variability of Volcanic Ash Eruptions and Impacts

2.1. Temporal Variability

Volcanic ash is a frequent hazard from volcanic activity. At least 46% of volcanoes that have erupted in the last 11,700 years have produced volcanic ash, in 71% of their eruptions (Siebert, et al, 2015). Both these proportions are likely underestimates because of lack of ash preservation in the environment. Estimates of volcanic ash frequency in eruptions can be made from global eruption databases such as that provided by the Smithsonian Global Volcano Program (GVP; https://volcano.si.edu/), and in Figure 3 we show a sample for the weekly records compiled by GVP for eruptions starting in the second-half of 2017.

There were 72 eruptions at 69 different volcanoes in 2017, with 31 starting in that year, a similar proportion to the average over the last 10 years (79 eruptions per year, 36 starting per year). For the 12 eruptions that started in the second half of 2017, Figure 3 shows the eruption duration and occurrence of ash events. The median duration of these eruptions is 6.5 weeks, close to the typical duration for Holocene eruptions of 7 weeks, and 11 of 12 eruptions produced ashfall. Five eruptions produced a single ash event at the start of the eruption, and six showed repeated ash events during the eruption, from a minimum of three events to a maximum of 20 events, with an average of 10 events per eruption. Ash was dispersed within 10 km of the volcano in three eruptions, between 10 and 100 km in three eruptions, and more than 100 km in one eruption, with no information recorded for four eruptions. These eruptions were all classified as moderate in size (between 0.001 and 0.1 km^3 of volcanic products) or smaller; larger eruptions with more widespread ash dispersion occur less frequently.

Figure 3 Timeline of volcanic eruptions occurring between 01/07/2017 and 31/12/2017 – blue line shows eruption duration, with thicker line for longer range ash dispersion, red dots show ash-producing events.

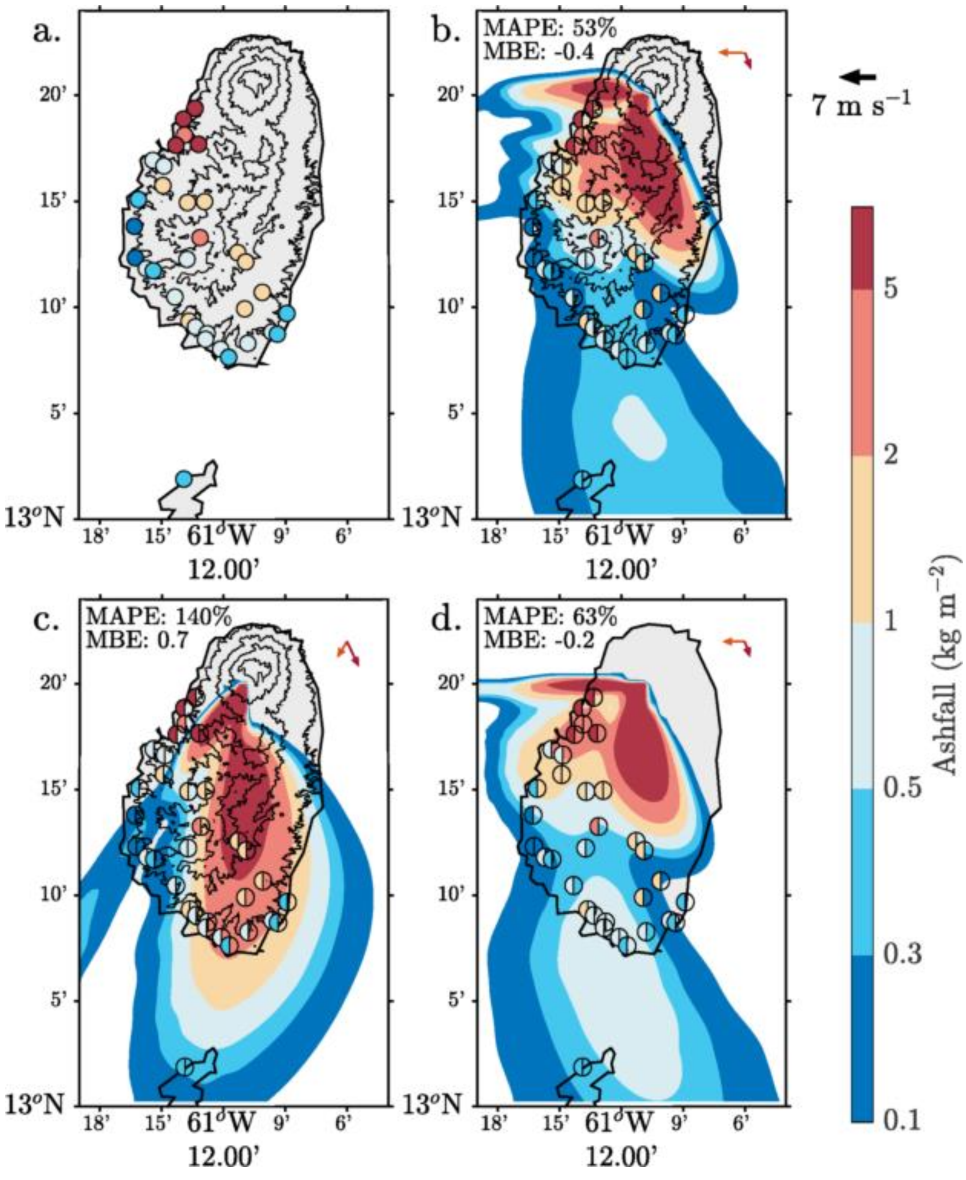


The picture emerging from this snapshot of recent eruptions is typical of the historic global pattern: most eruptions are relatively small, and volcanic ash is a hazard in most eruptions (Siebert, et al, 2015). Volcanic ash events typically occur repeatedly at days to weeks intervals during eruptions and ash impacts are felt relatively close to the volcano. Of the 12 eruptions in this sample, 11 occurred in countries classified as lower or middle income, reflecting the general trend of developing countries being disproportionately affected by volcanic hazards (e.g. Siebert, et al, 2015).

2.2. Spatial Variability

Ashfall from explosive events typical of extensive eruptions shows complex deposition patterns and localised impacts close to the volcano, where the effect of wind flow interacting with volcanic topography provides the major control on dispersion. These effects can be revealed with high-resolution ash transport modelling and detailed field sampling of ash deposits, as shown in detailed recent study of eruptions of Soufrière St Vincent in the Caribbean by Poulidis et al. (2018a). A reconstruction was made of a Vulcanian eruption on 26th April 1979 which had dispersed ash to the south over the island, and was measured in detail at the time (Brazier, et al, 1982). The deposit *mass accumulation* (mass per unit area) is shown in Figure 4; the deposit measurements are shown in Figure 4a, and compared with model simulations of the island topography and wind field best matching the conditions at the time of eruption (Figure 4b), the island topography and an alternative wind field typical for this region (Figure 4c), and no topography (a flat island) and the best-matching wind field (Figure 4d). The island topography controls deposition close to the volcano: flattening the island underestimates ash fall inland and overestimates ash fall on the western coast, and this effect is more significant for ash deposition than changes in the atmospheric wind field. The results highlight the impact of volcanic ash fall in small island settings, where inhabited areas are close to the volcano (typically within 10s km). The effects of topography on ash fall have been noted in other small island settings (Poulidis, et al, 2018b) and at longer distances from the volcano (Poulidis, et al, 2018a, Eychenne, et al, 2017; Watt, et al, 2015).

Figure 4 Ash fall distributions following the 26 April 1979 eruption of Soufriere St Vincent: (a) observed, (b-d) simulated from the meteorological-ash-dispersion model WRF, where the experiments are (b) best-matching wind profile; (c) alternative Wind profile (lower shear); and (d) flat topography. Observations are plotted over the contours using filled circles markers. In Panels b-d observations correspond to the left half of the marker and modelled values to the right. Topographic contours are shown at 100 m and every 300 m after that (after Poulidis et al 2018a).



2.3. Variability in Impacts and Risk

The impact of volcanic ash fall depends on vulnerabilities of infrastructure and communities (physical and social vulnerability), which in turn depend on the temporal and spatial footprint of ash fall events. Ash fall is the only volcanic hazard for which detailed studies of physical vulnerability have been made (Bonadonna, et al, 2018), because the physical impacts of ash can be characterised based only on the amount of ash (mass accumulation or thickness of deposit, or airborne concentration) without needing detailed knowledge of the dynamics of impact mechanisms. Consequently physical vulnerability to volcanic ash fall can be categorised by distance of exposed assets from the volcanic source, and this has been reported on extensively in Global Assessment Report 2015 (Jenkins, et al, 2015) and other studies focusing on infrastructure and agriculture (Wilson, et al, 2012). However, there is widespread recognition that consideration of social vulnerability, and crucially, the capacity of communities to respond and adapt to natural hazards, is essential to design effective strategies for volcanic risk reduction (e.g. Few, et al, 2017). Understanding social vulnerability requires attention to social structures (such as modes of governance and rules of land tenure, for example) as well as to patterns of variance in resources and livelihood assets at the individual and household level (Pelling, 2003; Few, 2007; Gaillard, 2008); these do not have any simple relationship with location relative to the volcano. We now present results from three case studies that highlight the critical role of social processes in response to volcanic ash impacts.

3. Case Studies of Extensive Volcanic Ash Fall

In this section we present detailed case studies conducted as part of the STREVA project (Strengthening Resilience in Volcanic Areas; www.streva.ac.uk), which demonstrate the extensive impacts of volcanic ash. Each example has a different focus: the role of intermittent ash fall on trajectories of vulnerability during the eruption of Soufrière Hills, Montserrat; community-led adaptations to volcanic ash fall impacts that were recurrent over many years during the eruption of Volcán Tungurahua, Ecuador; and long-term impacts and benefits from a relatively short eruption of La Soufrière, St Vincent. Each study combines physical and social science research framed as a forensic analysis (Burton, 2010).

3.1. Soufrière Hills Volcano, Montserrat (1995 – present)

The island of Montserrat is located in the Lesser Antilles Arc of the Caribbean, and is approximately 16 km (North – South) by 10 km (East – West) in area, with the Soufrière Hills Volcano situated approximately 4 km from the southern end. The eruption of Soufrière Hills began on 18th July 1995, and continues to the present day. Since 1995, the volcano has erupted over 1 km^3 magma as a series of lava domes that have been progressively destroyed by explosive activity or gravitational collapse (Wadge, et al, 2014). The whole eruption episode consisted of five phases of lava extrusion, lasting months to years, interspersed with periods of repose with similar durations. Phase One (November 1995 – March 1998) was the initial phase of extrusive activity, and included lava dome growth and collapse to form block-and-ash flow PDC, periodic ash eruptions, and a short series of Vulcanian explosions. Volcanic hazards in later phases included repeated PDC and explosions, interspersed with isolated Vulcanian eruptions producing ash deposition over the island. Volcanic ash falls occurred regularly during the eruption, with particularly large events in 2003 and 2008 and near-daily ash events from October 2009 to February 2010 (Sword-Daniels, 2011). During Phase One, a set of exclusion zones were emplaced to protect life, and resulting evacuations displaced residents from the south of the island to the north. Following an intense phase of volcanic activity in 1997, many displaced Montserratians accepted a migration package to the UK and elsewhere in the Caribbean. A population of over 10,500 was reduced to 2,850, increasing to 4922 by the 2011 national census.

Trajectories of vulnerability of Montserrat residents during the eruption were studied by Hicks and Few (2015), and a synthesis of their results is presented here. They used information obtained through specialist and multidisciplinary discussion groups as part of a STREVA project workshop in Montserrat in September 2012, supplemented by 16 post-workshop interviews. Repeated volcanic ash fall events were highlighted as having negative consequences for two of the most vulnerable groups identified through their study. 'Assisted passage migrants to the UK' (those accepting the migration package offered in 1997) cited volcanic ash impacts on health (particularly of children) as a significant concern. A study by Forbes et al (2003), conducted in 1998, reported that, "children who lived in areas with moderate or heavy exposure to ash since July 1995 reported more respiratory symptoms and use of health services for respiratory problems than children who had never lived in these areas", and furthermore, "asthma was frequently cited as a medical condition among families who left under the Assisted Passage Scheme". Those 'poorer non-migrants resettled in the North' (following Phase One evacuations) reported that ash fall events could sometimes result in the destruction of their crops overnight, and this limited the development of agriculture and diversification into new agricultural practices (Halcrow Group and the Montserrat National Assessment Team 2012). Hicks and Few (2015) also noted that heavy ash falls over the island in 2006 necessitated significant investment from the government of Montserrat for clean-up operations, and the resulting employment opportunities encouraged immigration, contributing to the population increase noted in the 2011 census.

Ash fall over the north of the island was a continued impact until recently, with infrastructure built during the recovery period needing constant cleaning, replacement and repair (Wilkinson, 2015). Most buildings (and homes) have slatted windows, which allow ash to enter buildings because they cannot be properly sealed (Sword-Daniels, et al, 2014). Despite these challenges, interviews have shown that affected residents try to be positive "They say things like '*We're fine.*' '*We're living with ash.*' '*We've been living with it for a couple of years.*' '*We're okay.*' '*We're alive.*' '*We're still here*.' " (Sword-Daniels, 2011). Purposeful adaptations have also taken place over the timescale of ash fall activity, including regular information about ash fall and impacts on water supplies broadcast on radio news, installation of backup electricity supply systems, and building changes including greater use of air conditioning (rather than open windows that allows ash ingress) and reduced use of metal in construction, which corrodes in the presence of volcanic ash (Sword-Daniels, 2011).

3.2. Volcán Tungurahua, Ecuador (1999-2016)

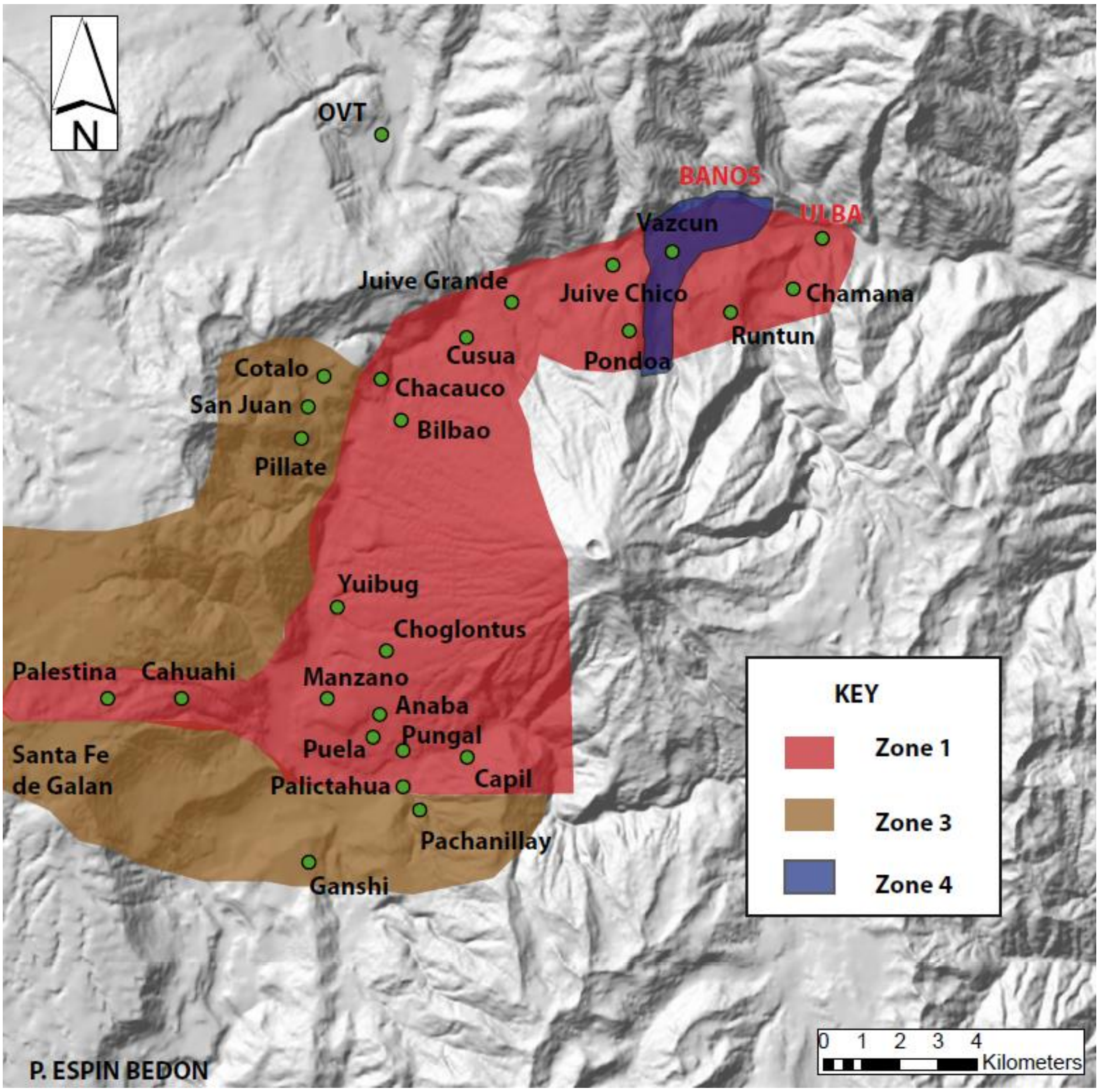
Volcán Tungurahua is located on the Eastern Cordillera of the Ecuadorian Andes (long: 78.45W, lat: 1.47S, alt: 5023 masl.) and covers part of the territory of two provinces, Tungurahua and Chimborazo. The volcano is surrounded by several towns at varying elevations with more than 30,000 people living in both rural and urban areas where the volcano poses a threat to life. More distant areas that experience volcanic ash falls have a population of more than 200,000 (Mothes, et al, 2015).

Volcanic unrest started at Tungurahua in April 1999, and the first explosive activity took place in October 1999, which was followed by a forced evacuation that displaced approximately 26,000 people for 3 months (Tobin and Whiteford, 2002). From 2000 to 2006 volcanic activity was characterised by intermittent periods of intense seismic activity followed by small Strombolian eruptions and ash falls, with subsequent rainfall-triggered remobilisation of ash as lahars, interspersed with periods of quiescence (Arellano, et al, 2008). During these years, intense ash falls and lahars impacted farmers on the slopes of the volcano, destroying crops, killing animals and damaging access roads and other infrastructure (Le Pennec, et al, 2012, Sword-Daniels, et al, 2014). In August 2006 a series of Vulcanian explosions was followed by a stronger sustained explosive eruption, that lasted over 16 hours. This eruption produced several PDCs, killing 6 people and destroying more than 50 homes on the flanks of the volcano (Mothes, et al, 2015; Valencia, 2010). The impact caused by the 2006 eruptions prompted the state and Non-Governmental Organisations (NGOs) to build resettlement homes for those living in high risk areas (Reliefweb, 2006). Despite this, hundreds of families continued to live and/or work on the flanks of the volcano to sustain their livelihoods. After the August 2006 eruption, the volcano showed intermittent activity, predominantly producing ash fall that impacted agriculture and aviation routes. A new phase of energetic and more frequent Vulcanian eruptions occurred between August 2012 and August 2014. Between 2010 and 2016, the eruptive episodes became shorter in duration but marked by more intense explosive activity (Hall, et al, 2015). Mothes et al (2015) identify 22 discrete explosive phases since the start of the eruption in 1999, and there has been no explosive activity since 2016.

Armijos and Few (2015a), Armijos et al (2017) and Few et al (2017) have studied extensive impacts of volcanic activity, the evolution of risk management and dynamics of vulnerability over the duration of the eruption of Tungurahua. These studies drew on 67 semi-structured interviews, a 411-household questionnaire survey, conversations with local residents and participant observation, conducted over a four month period at the end of 2013 (Figure 5).

Agriculture is the primary occupation in communities that live on or near the volcano, with farm smallholdings mostly of 1 – 10 ha and used for arable and livestock production (Chiriboga, 2009). A large variety of crops are produced on land ranging from 1500 to 4000 m above sea level, including maize, potatoes, beans, peas, onions, tomatoes, citrus fruits, apples, plums, tamarillo and sugar cane. Livestock production includes dairy and beef cattle and intensive chicken farming. Most households also raise chickens, guinea pigs and pigs for their own consumption and occasionally for sale (Valencia, 2010).

Figure 5. Map of communities located around Tungurahua surveyed by Armijos and Few (2015a) and the zonation they used to assess ash impacts (note that Zone 2 is in the resettlement area to the east of this map). Map drawn by Pedro Espin Bedón.



Repeated ash fall has had a profound effect on the social vulnerability of the communities near the volcano. Almost all survey respondents (including those in resettlements in zone 2, where many livelihoods are still based on agriculture), reported that they had been repeatedly affected by ash; 84% of those living at higher altitudes on the volcano stated that they 'always' or 'almost always' receive ash fall when the volcanic activity generates ash (Figure 6). Repeated ash fall has disrupted agricultural production, and the amount and types of crops, and the numbers of livestock, have decreased. The effect of ashfall on arable production depends on the type of crop, its stage of maturity, the amount of ashfall and the type of ash. According to some of the local farmers interviewed, the most sensitive crops are large-leaved crops that collect and retain ash, despite wind or rainfall, including potatoes, pumpkins, tomatoes and fruit trees (Figure 7). The stage of maturity is also important. For example, maize is generally thought to be more resistant to ash, but can be severely affected if ash falls before flowering or when the maize kernel is in early stages of development. Different types of ash vary in the damage they cause, because finer particles are retained for longer or 'cemented' on to leaf surfaces. Some of this local knowledge is also recognised in scientific studies of ash impacts (e.g. Ayris and Delmelle, 2012). In the survey, 66% of households on the volcano that own animals reported that today they have fewer animals than in 1999. This is in part due to repeated volcanic ash events contaminating grazing land. When cows, sheep and guinea pigs eat grass contaminated with volcanic ash it affects their teeth and intestines, and they can become ill, lose weight, produce less milk and even die.

Figure 6 Proportion of survey respondents affected by volcanic ash around Tungurahua since 1999 (after Armijos and Few, 2015a).

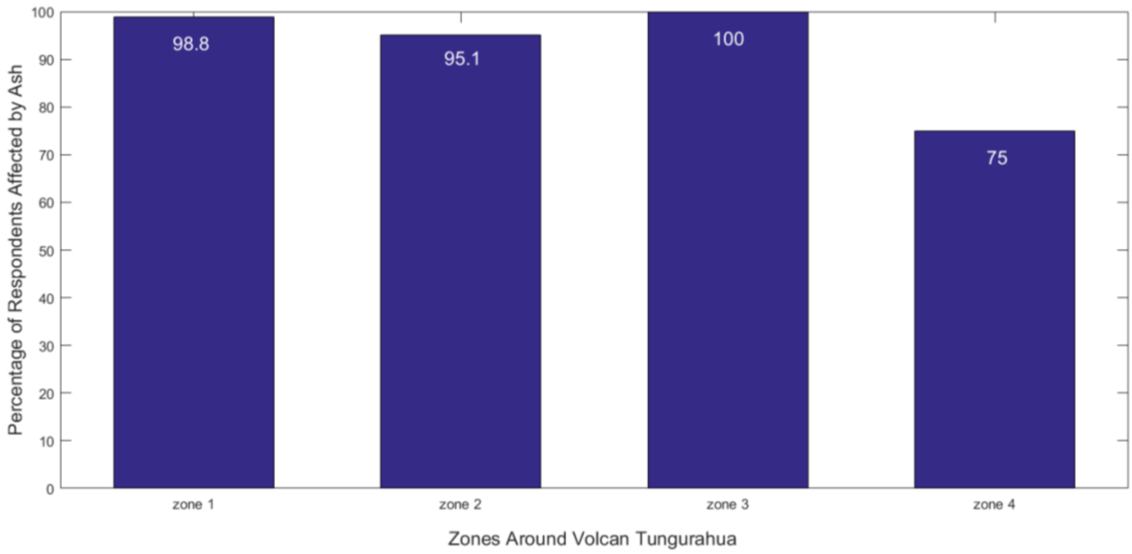


Figure 7 Tomate de Árbol trees in Pondoa (Zone 1) covered in grey and white ash in 2014 (Maria Teresa Armijos).

Local farmers who have lost crops and animals have gained significant knowledge about the different types of ash and their effects on different crops. Through experience and long-term exposure to volcanic ash, they have also been able to identify the crops that are able to resist ash fall (Valencia, 2010). Farmers remaining on the slopes of Tungurahua have responded by focusing their agricultural production on maize and by harvesting it earlier (the longer a single crop is left to mature the more chance that crop could be lost or damaged by ashfall). This change was also possible because of an existing market demand for fresh maize, but has negative consequences in denying the farmer both a source of subsistence and of seed for replanting. Many farmers occupying high-altitude land impacted by ash have changed cash crop production from potato to the spring onion crop *Allium Fistulosum,* reporting that the shape of the spring onion plant's leaves make it less likely to retain ash and thereby less susceptible to ash damage than potato. In 1999, potato was the most important crop for 24% of households, while this figure had dropped to 10% in 2014. The equivalent figures for spring onion show a change from 5% to 27%. Other adaptations include increased areas of covered greenhouses for the production of tomate de árbol and highland papaya. The most common measure to stop animals from getting ill or dying after ash deposition is to prevent them from eating contaminated grass. Immediately after an ash eruption, it is not uncommon for farmers to run to the fields and cut grass and store it indoors before the ash has fallen, and afterwards most farmers would try to cut, clean and feed ash-free grass to their animals. Another common practice is to cut maize stalks, clean them and use these as feed. In all affected areas, respondents considered smaller animals to be a more important commodity since 1999, in particular noting that the health of chickens is less affected by ash, and they are cheaper to replace than larger livestock.

3.3. Soufrière St Vincent (1979)

The island of St Vincent is approximately 26 km (North-South) by 15 km (East-West) in area, with La Soufrière volcano located approximately 4 km from the northern end of the island. La Soufrière has an unusually rich record of historical volcanic activity with six certain and two possible eruptive episodes recorded over the last 300 years (Siebert, et al, 2015; Robertson, 1995). Detailed contemporaneous accounts of volcanic activity can be found in archival records and have been used to reconstruct the impacts of the 1902-03 eruptions, which significantly affected not only strongly St Vincent but also the neighbouring island of Barbados some 240 km away (Pyle, et al, 2018; Poulidis, et al, 2018a). The 1979 explosive eruption commenced on 13th April and continued for two weeks, with 11 ash-producing events and minor PDC. The dispersal of ash from all but two events was to the East, following the usual Trade Wind patterns. Unusually, the 26th April eruptive plume was dispersed to the south, producing significant ash deposition across the island (Brazier, et al, 1982). In response to the first ash event, the Government sent trucks to evacuate those in the north of the island. Others self-evacuated using boats or other vehicles or on foot, with reports noting that ash reduced traction for road vehicles. A total of 59 Shelters were set up at schools in the south of the Leeward (West) and Windward (East) sides of the island and around 20,000 people stayed for up to 4 months.

Armijos and Few (2015b) have studied the extensive volcanic impacts and recovery from the 1979 eruption, using 46 semi-structured interviews, 5 group interviews, a 400-household survey, and other conversations with local residents, across 12 villages in the northern Windward and Leeward sides of the island. Of particular note was the long-term damage inflicted on vulnerable roofing materials, for example (from Armijos and Few, 2015b): *"All the trees were burnt. […] some of the houses fell because of the material. Even some galvanised, the softer type, those were damaged […] The metal itself had started eroding because of the ashes"*

Water resource was a significant issue with contamination by ash leading to supply disruption for 4-5 months and cascading impacts for feeding cattle, and increased erosion on uncleared road surfaces, weighted with ash. During the recovery from the eruption, assistance from different sources including the state, family and friends seemed to have been available at different levels; survey data shows that about 15% of households received assistance from the government and 24% from family and friends. Prominent among respondents' comments was state provision of new roofing materials to replace that rusted due to exposure to ash and rain.

Volcanic ash fall significantly affected agriculture, which was, and remains, the most important source of income in the north of the island. The day that local residents evacuated from their villages, as instructed by the authorities, animals were set free so that they could roam and feed. During the months people stayed at the shelters they made regular visits to their villages to tend to their animals and their properties, but still lost many animals due to illness, lack of water, food and theft. For example, (from Armijos and Few, 2015b) "…*They found a lot of them dead, so they had to buy them [new livestock]. The animals had nothing to eat because the grass was covered with ash."* Interviewees noted that when they returned to their villages after the eruption, they spent considerable amounts of time cleaning up their houses and their fields. Mixing the ash that had fallen into the soil and preparing the fields for the crops became a priority. However, the return also coincided with the rainy season, which helped the clearing and 'mixing' of ash with soil.

The state provided assistance for agricultural recovery by sending plants, seeds and manure from the capital Kingstown, located in the south of the island and unaffected by ash fall. Other organisations assisted farmers in planting rapidly growing crops such as potato vines and peanuts. Nonetheless, it took several months before people were able to harvest crops and thus obtain income.

Despite the difficulties encountered when going back to the villages, many farmers described the first harvest after they returned as excellent, attributed to both improved soils and loss of pests as a consequence of the ash. These perceptions and experiences were exemplified by the following two quotes (from Armijos and Few, 2015b). *"Well we got good crop when we started planting again. It seemed like manure was in the soil. So it was good for the crops. After a whole year a lot of things plant up and they grow well."*

"I remember that when some people returned and they started to farm, the crops that they reaped was more fruitful so they were saying that the ash was like manure. It was one of the most fruitful times for farmers after the eruption."

4. Dynamic and extensive volcanic risk: ash fall impacts, benefits and interventions

In this final section, we synthesize broad-scale and case study knowledge of volcanic ash impacts to draw out knowledge gaps and lessons learned. The analysis of volcanic eruption records and the detailed case studies of volcanic ash impacts strongly highlight the dynamic and extensive nature of volcanic activity. The emerging view is that many eruptions are not discrete cataclysmic events, but persist over timescales that impact livelihood maintenance and development trajectories, with repeated bursts of activity, including the volcanic ash falls that are the focus of this paper. Our case studies and high-resolution modelling show that while eruptive events are of short duration, their impacts can extend over longer periods of time, and be highly spatial variable on the scale of individual communities living in close proximity to volcanoes.

The combination of extensive impacts on livelihoods and different types of hazard events with rapid switches between them, and the interaction between fresh deposits of ash and meteorological variables (notably wind and rain) mean that volcanic risk is highly dynamic. The case studies presented here highlight that discrete events include PDC and lahars as well as ash fall events, each extensive in their recurrent impacts yet requiring different mitigation of their threats. These events are themselves linked to the longer-term evolution of activity at the volcano, such as the different phases of dome growth at Montserrat associated with different intensities and frequencies of ash fall events and PDCs; or the shallowing of the magma source during the eruption of Tungurahua that is linked to the switch from Strombolian to more violent Vulcanian explosive events. Impacts of ash fallout events can extend long beyond the deposition event itself, as the ash may be remobilised into lahars during rainfall events; and into ash storms by wind; both sets of process may extend the footprint and impact of the hazard well beyond the areas originally affected by ash.

Typical timescales of extensive volcanic impacts of weeks to months necessitate risk mitigation strategies that recognise the need to maintain livelihoods, which in turn requires engagement with affected communities (Gaillard, 2008; Few, et al, 2017). The critical livelihood impact of ash focused on in these studies is on agriculture in small communities, because this provides most of the food consumed in the developing world. The comparable timescale of extensive ash activity to agricultural production cycles means that repeated small-scale ash events can eliminate production of critical cash crops, and that restarting production can be a lengthy process due to the need to clean-up or remove of surface ash by incorporation into the soil. In our case study examples, ash impacts have led to changes in arable agricultural cropping, which in turn can create problems in local economies due to the overproduction of plant types that are more resistant to ash, although more diverse higher-value crops may still be grown with farmers accepting greater risk for higher reward (Few, et al, 2017). Ash impacts have also resulted in changes to livestock type, both in size, and to non-grazing animals, through recognition of reduced health impacts and lower replacement costs. In more extreme situations, livelihoods have changed where this is possible, for example, from farming to fishing in St Vincent (Armijos and Few, 2015b). These changes necessitated by the impacts of volcanic ash have negative consequences for those affected including loss of income, reduced food production of lower nutritional value, and increased investment to learn new skills and buy equipment needed for new livelihoods: these all critically limit ability to reduce poverty and hunger (SDG 1 and 2). Nonetheless, a key feature across all case studies is the adaptation of farmers experiencing extensive ash events as they observe and learn about the ash impacts. This creates practical and implementable strategies for livelihood maintenance, based on knowledge that can be integrated with scientific research (e.g. Balay-As, et al, 2018).

The most complete scientific research on impacts of volcanic ash on agricultural systems and the environment has been in Patagonia, in the aftermath of major explosive eruptions of Hudson (1991), Chaiten (2008), Puyehue Cordon-Caulle (2011) and Calbuco (2015). The volcanoes are in Chile, but the extensive impacts are almost all in Argentina (Watt, et al 2009; Wilson, et al 2012a,b). These studies include assessments of immediate impacts in particular settings, broad-scale and short-term impacts on livestock and specific surveys of impact and recovery on particular ecosystems. Physical impacts include landscape changes influencing water runoff, changes to lake and river system morphology through ash transported as sediment load, and longer-term changes in soil structure (see Delmelle, et al, 2014). Chemical impacts include release of water-soluble salts from the ash to the environment (notably fluoride), and release of nutrients as the volcanic glasses in the ash weather (including potassium, calcium, phosphorus and sulphur), though whether this occurs, and its rate, depends on environmental factors including climate and rainfall (Martin et al., 2009; Delmelle, et al, 2014; Ayris and Delmelle 2012). Over the months-to-years timescales of extensive ash deposition, nutrient and salt release and soil modification are comparable.

Physical and social science studies of ash impacts on agriculture highlight the beneficial effects of ash deposition through increased crop yields. However, further research is needed to properly characterise the persistence of these benefits. The case studies presented here suggest that these benefits may be greatest in tropical regions where there is rapid transport of nutrients from ash in soils due to high rainfall and favourable weathering conditions, and may be much reduced in the arid conditions of Patagonia where these processes occur much more slowly (Delmelle, et al, 2014).

Our case studies of volcanic ash fall have highlighted the critical role of interventions by the state or other actors in mitigating extensive natural hazard impacts. The months-to-years timescales of extensive ash impacts are aligned with time required for governance systems to react and provide assistance, and also for the development of informal processes that support formal risk management systems (Armijos, et al, 2017). Timely provision of assistance in the form of rebuilding materials for housing, animal feed, and new plants and seed for restarting arable production supported the recovery from ash eruptions of Soufrière St Vincent and Tungurahua. During the early years of the Tungurahua eruption, engagement by scientists with local communities to rebuild trust following the initial forced evacuation led to the creation of a system of community volunteer volcano watchers (the *vigías*) which improved community knowledge of extensive volcanic activity (Stone, et al, 2014; Mothes, et al, 2015). Improved knowledge of extensive hazards has supported the continuation of farming activities on the volcano, that led in turn to purposeful adaptations of agricultural practice that support livelihoods during long-lasting eruptions. Local systems including self-evacuation during explosive episodes, and support from local authorities in commuting between farmed areas and resettlement homes, are part of a broader informal network of risk management that has developed from these interventions at Tungurahua (Armijos, et al, 2017). These studies highlight the critical connection between the development of community knowledge of impacts and the adaptations made to maintain livelihoods, and purposeful and timely interventions, that together support development of longer-term resilience to extensive hazards.

Recognition of the extensive nature of volcanic ash impacts and other volcanic hazards such as PDC and lahars has direct implications for disaster risk reduction policy and practice. Volcanic eruptions may be long-lasting with repetitive pulses of activity and recurrent impacts, so provision of relief, and management of risk to life need to anticipate the long-lasting and ongoing costs of taking action. Flexible planning is needed to support communities in regions where impacts are highly spatially and temporally variable. Our case studies highlight that long-term exposure to volcanic activity that does not threaten life can still severely impact people's wellbeing. Risk management practice needs to acknowledge that while people may not want to be relocated or viewed as vulnerable (because of attachment to place and potentially worse alternatives), repeated ash eruptions will reduce their ability to maintain their livelihoods, including food production. Our studies highlight how during prolonged volcanic activity, communities affected repeatedly by ash fall can develop strategies to mitigate the impacts on agricultural production, and thereby maintain livelihoods. Successful risk management needs to incorporate this location-specific knowledge, and build on these opportunities for engagement with affected communities to improve outcomes and translate learnings to new settings. Extensive volcanic activity may necessitate periodic short relocations to mitigate immediate threat to life from eruptions that punctuate the broader risk landscape. In such cases,- risk management interventions should focus on how to support people and their livelihood assets during transient relocation, to maintain livelihoods in the face of extensive hazards.

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