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Drivers of crop impacts from tephra fallout: insights from interviews with farming communities around Tungurahua volcano, Ecuador

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Abstract

Agriculture is an economic and social pillar for the least developed countries. When these regions host volcanoes that exhibit explosive behaviour, a serious risk for agricultural production arises as crops endure various impacts from tephra fall. In order to gain new insights into the factors that govern tephra impacts on crops, we collected farmers' perceptions of crop damage and production loss due to exposure to tephra fallout in 15 villages affected by the 1999–2014 eruptions of Tungurahua volcano, Ecuador. Crop type and developmental stage—both influenced by altitude—strongly modulate the level of tephra-induced impact. Using these observations, we illustrate how crop vulnerability fluctuates spatially and temporarily in the surveyed area. The study also highlights that fine tephra (<63 µm) is more harmful to crops than coarser particles. Farmers have responded to the tephra hazard by favouring crops more resistant to tephra, a practice that has reduced crop diversity.

Resumen

La agricultura es un pilar económico y social para los países en vías de desarrollo. Cuando estas regiones albergan volcanes que presentan un comportamiento explosivo, surge un grave riesgo para la producción agrícola, ya que los cultivos sufren diversos impactos por la caída de tefra. Con el fin de obtener nuevos conocimientos sobre los factores que rigen los impactos de la tefra en los cultivos, recogimos las percepciones de los agricultores sobre los daños en los cultivos y las pérdidas de producción debidas a la exposición a la caída de tefra en 15 pueblos afectados por las erupciones del volcán Tungurahua (Ecuador) entre 1999 y 2014. El tipo de cultivo y la etapa de desarrollo -ambos influenciados por la altitud- modulan fuertemente el nivel de impacto inducido por la tefra. Utilizando estas observaciones, ilustramos cómo la vulnerabilidad de los cultivos fluctúa espacial y temporalmente en la zona estudiada. El estudio también destaca que la tefra fina (<63 µm) es más dañina para los cultivos que las partículas más gruesas. Los agricultores han respondido al peligro de la tefra favoreciendo los cultivos más resistentes a la tefra, una práctica que ha reducido la diversidad de cultivos.

Keywords: Tephra; Hazard; Agriculture; Tungurahua

1 Introduction

Developing countries in Central and South America, Southeast Asia, and Oceania host a large number of volcanoes exhibiting explosive styles [Simkin and Siebert 2000]. Repeated periods of unrest have endowed vast areas with tephra deposits on which fertile volcanic soils have formed. Agriculture in these regions flourishes and typically represents one of the most important economic sectors [FAO 2021]. Paradoxically, the tephra falls that underpin productive volcanic soils pose a major threat to farming. Tephra affects crops and pastures, livestock health, assets, and infrastructure in a variety of ways, on local (a few km^2 for small but frequent eruptions) to regional (hundreds of thousands km^2 for large but rare eruptions) scales [Blong 1984; Mendoza and Cabangang 1992; Neild et al. 1998]. The resulting losses, notably in the production of crops and livestock, may undermine the resources that smallholder farmers can allocate for investment in livelihood activities and may jeopardise food security.

The Food and Agriculture Organisation (FAO) emphasises the urgent need to build agricultural systems in developing countries that are more resilient to the impacts of natural hazards [FAO 2021]. This also applies to volcanic eruptions. A sound understanding of impacts of tephra on agriculture is necessary to inform appropriate risk reduction, management, and long-term recovery strategies in regions exposed to volcano-related hazards [Jenkins et al. 2015]. The issue is exacerbated in developing countries where a large percentage of the population continues to live in rural areas

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and is reliant on farming [Atchoarena and Gasperini 2003]. However, our knowledge regarding the nature and extent of tephra-induced damage and production loss are limited to circumstantial evidence and a relatively small number of impact investigations after an eruption [e.g. Wilson et al. 2007; 2011; Blake 2015; Craig et al. 2016a; b].

Post-event impact assessment studies are used to collect data on effect, hazard, and vulnerability, which can guide impact and risk analysis models [Wilson et al. 2014; Craig et al. 2016b; 2021]. Impact on the exposed asset is understood to be a function of hazard and vulnerability. A particularity of the tephra hazard is that it typically shows a damage gradient due to the thinning of the deposit with distance from the source volcano. For tephra impacts on agriculture, thickness of the fall deposits is the metric commonly selected to assess the severity of a tephra fall at a site (i.e. hazard intensity) in relation to damage [Neild et al. 1998; Wilson et al. 2007; Craig et al. 2016b; 2021]. For crops and livestock, other tephra properties such as particle size and the presence of soluble compounds on particle surfaces may also modulate the impact [Ayris and Delmelle 2012].

In addition to tephra characteristics, site-specific biophysical factors such as climate and vulnerability of the exposed agricultural system are strong determinants of the type and extent of damage that results from tephra fall on crops. An agricultural system may be viewed as a specific combination of various cropping and livestock rearing systems, both of which are accompanied by a set of production means and a specific workforce [Spedding 1988]. Agricultural systems are diverse and thus vulnerability to tephra varies widely across different agro-systems. This calls for situation- and context-specific post-eruption studies of vulnerabilities. To date, most of the information available pertains to agriculture in temperate environments [Wilson et al. 2007; Craig 2015; Craig et al. 2021].

By comparison with observations made for other types of natural hazards [FAO 2021], crops represent the agricultural subsector most likely affected by tephra fall. Arguably, the description of crop vulnerability to tephra fall is critical to volcanic risk and impact assessment for agriculture [Wilson et al. 2007; Craig et al. 2021]. In this study, we document the damage and production loss inflicted by tephra fall to various crop types in the vicinity of Tungurahua volcano (Ecuador), an edifice in the tropical Andes which was active between 1999 and 2016. We interviewed farming communities which had been repeatedly exposed to the tephra fallout in order to (i) shed light on the volcanic and non-volcanic factors that drive impacts on crops from tephra fall and (ii) examine the temporal and spatial variability of crop vulnerability to tephra falls across the surveyed area.

2 Study site and methods

2.1 Tungurahua volcanic activity

Tungurahua is a 5023-m-high, steep-sided active stratovolcano, located 140 km south of Quito on the Eastern Cordillera of Ecuador (Figure 1). It is one of the most active volcanoes of the Northern Andes [Hall et al. 1999; Le Pennec et al. 2008; Eychenne et al. 2012]. In the last ∼500 years, Tungurahua has had five major episodes of explosive activity, ranging in Volcanic Explosive Index (VEI) between 2 or 3 [Newhall and Self 1982]. Tungurahua's magma varies from andesitic to dacitic in composition [Hall et al. 1999; Hall and Mothes 2007; Samaniego et al. 2011].

The last period of volcanic unrest took place between 1999 and 2016 after a repose of 80 years. The unrest alternated between phases of quiescent and explosive activity, with notable Strombolian and sub-Plinian events in November–December 1999, August 2001, July and August 2006, February 2008, May and December 2010, August 2012, July 2013, February 2014, November 2015, and February 2016 [Eychenne et al. 2012; Hall et al. 2015; GVP 2017a; 2018]. These eruptions of Tungurahua produced tephra fall that typically affected a sector west and southwest of the volcano [Eychenne et al. 2012; 2013; Bustillos A et al. 2016]. The most powerful explosive event took place on 16–17 August 2006 and generated a 16–18 km-high eruption column with tephra deposited across a 3000-km^2 area [GVP 2006; Eychenne et al. 2012]. This explosive activity persisted through 2007 and 2008 and led to the vigorous February 2008 eruption, which forced the evacuation of 2000 people [GVP 2008]. After a quiescent period in 2009, Tungurahua erupted again in 2010, with the following six years being punctuated by short-lived violent Strombolian to Vulcanian episodes that sent tephra plumes as high as 10 km in the atmosphere [GVP 2015; 2017b]. The last two significant eruptions accompanied by tephra fall occurred in November 2015 and February 2016 [GVP 2017a; 2018].

2.2 Agricultural landscape in the Tungurahua region

The agricultural landscape around Tungurahua is characterised by relatively small farms, typically 1–10 ha in size [INEC 2008; de la Comunidad Andina 2009; FAO 2010a], which produce crops and raise livestock for dairy and beef. The well-documented fertility of volcanic soils [Shoji et al. 1993; Dahlgren et al. 2004; Delmelle et al. 2015], combined with the climate in the Tungurahua sierra (i.e. average temperature of 16–17 °C, annual precipitation between 400 and 1000 mm, and relative humidity between 50 and 85 %), provides suitable conditions for cultivation of various crops and fruit trees [Villavicencio and Vásquez 2008]. Prior to 1999, agriculture on Tungurahua volcano's slopes was the main source of production for markets in Ambato and Riobamba, the capital cities of Tungurahua and Chimborazo provinces, respectively (Figure 1).

About 25 000 inhabitants reside in the high-risk zone of tephra fall from Tungurahua volcano, but a larger and mostly rural population of ~300,000 may have been impacted by the 2006 tephra fallout [FAO 2010a; Mothes et al. 2015]. In particular, the agricultural sector suffered severe losses from tephra fall. For example, the 16–17 August 2006 eruption affected ~900,000 ha of cultivated lands and pastures, resulting in a ~26 million US$ economic deficit [FAO 2010a]. Grazing livestock (mainly cattle) was also affected as ingestion of tephra and malnourishment resulted in weight loss, decreased milk production, and sometimes death [FAO 2010a; Armijos and Few 2015; Few et al. 2017].

2.3 Field survey

The field survey took place in November and December 2014 in a ~300-km^2 sector of potential tephra fall impact from Tungurahua volcano, as delimited by the Instituto Geofísico of the Escuela Politécnica Nacional (Ecuador) [Samaniego et al. 2008] for explosive eruptions typified by a VEI of 2 or 3, which corresponded to tephra deposit thicknesses of 10–19 and 20–29 mm during the August 2001 and August 2006 eruptions, respectively. The survey was designed to obtain information on the main crops cultivated, crop-specific calendars, tephra hazard, tephra fall effects on crops, and coping strategies and adaptations deployed by farmers during and after the eruptions. Data were collected using a structured questionnaire (provided as Supplementary Material). A structured questionnaire is the primary measuring instrument in survey research and it has been used in multiple risk and impact perception studies related to natural hazards [Gregg et al. 2004; Rego et al. 2018; Shen et al. 2020]. The questionnaire was created following established guidelines [Stats NZ 1992; Manzano et al. 1996] and checked by two social scientists from the Escuela Politécnica Nacional. Ancillary information was compiled if the farmers qualified their answers during the face-to-face interview.

The number of farmers (n) to be interviewed in each village was decided based on Equation 1 [López 2004], which derives from Slovin's method for random sampling of a population with an unknown underlying distribution [Guilford and Fruchter 1973; Yamane 1973]:

$$n = N/((N-1)\times K^2+1) \tag{1}$$

where N is the number of households and K the error margin, i.e. a measure of the statistical dispersion around the actual population value. Typical K values are in the range 2–10 % [López 2004], resulting here in n = 535–1121. Due to time constraints, we chose to reduce the number of interviewees by assuming a higher K value of 20 %. In total, 241 farmers were interviewed in face-to-face conversations. We conducted the interviews in Spanish with the help of local agronomists and master's students who were trained prior to going to the field. Most of the interviews were done during weekends when farmers are usually more available. Prior to conducting the interviews, the village communities were visited informally at least once, which contributed to build trust and improved the quality and depth of the gathered information. Participants were informed as to the purpose of the research before proceeding to the questionnaire. Farmers' consent was acquired before the survey, and their anonymity was established.

The 241 respondents (women and men of different ages and social status) are smallholder farmers, i.e. managing small-scale farms (<5 ha) mainly based on family labour and which were repeatedly exposed to tephra fall from Tungurahua volcano during the period 1999–2014. They were distributed across fifteen villages located in Tungurahua and Chimborazo provinces, at altitudes ranging from 2000 to 3600 m a.s.l. and within 15 km west of the volcano (Figure 1). The villages are: Juive Grande, Cusúa, Bilbao, Yuibug, El Altar, Puela, Choglontus, El Manzano, Cotaló, Pillate, San José del Chazo, Sabañag, Hualcanga, El Sanctuario, and Santa Fe de Galán. The altitudes, coordinates, and distances from the volcano of these localities, number of households per village, and number of farmers interviewed are provided in Table S1 (Supplementary Material).

3 Results

3.1 Main crops cultivated and crop-specific calendars

The main crops cultivated in each of the fifteen villages surveyed are listed in (Table 1). Corn dominated in eleven villages. Potato, frijole, and/or tamarillo (also called "tree tomato") were the next most important crops in six villages. Apple was cultivated only in El Altar and Puela. Potato and/or white onion replaced corn as the principal crop at high-altitude (>3450 m a.s.l.), i.e. Sabañag, Hualcanga, El Santuario, and Santa Fe de Galán. The smallholder farmers also grew secondary horticultural crops including fava bean, black seed squash, blackberry, and deciduous tree fruits such as peach, pear, tangerine, and/or greengage.

A crop calendar contains information on the crop development cycle (i.e. vegetative growth, reproductive, and ripening phases) of the locally-adapted crop and is used to plan such agricultural operations as sowing, ploughing, fertilising, weeding, and harvesting [FAO 2010b; Yulianti et al. 2016]. Based on the farmers' explanations, we constructed a basic crop calendar for each type of main crop cultivated in the surveyed area (Figure 2). In Choglontus, Cotaló, and El Santuario, the sowing period of corn, frijole, black seed squash, and fava bean begins between May and August, depending on location, and lasts for two to three months. Potato, white onion, tamarillo, fava bean (cultivated

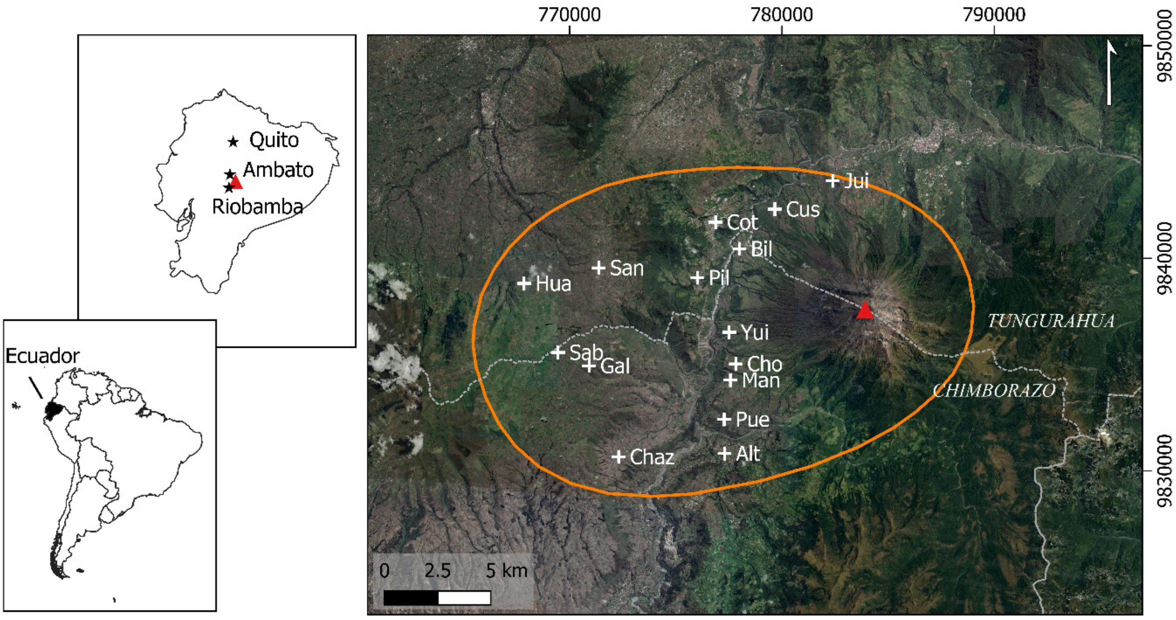

Figure 1: Location map. Inset shows location of Tungurahua volcano in Ecuador. The orange line delineates the study area (see text for explanations). White crosses represent the 15 villages surveyed: Jui:Juive Grande; Cus: Cusúa; Bil: Bilbao; Yui: Yuibug; Cho: Choglontus; Man: El Manzano; Pue: Puela; Alt: El Altar; Cot: Cotaló; Pil: Pillate; Hua: Hualcanga; Sab: Sabañag; Gal: Santa Fe de Galán; Cha: San José del Chazo: San: Sanctuario. The dashed white line shows the limit between Tungurahua and Chimborazo provinces. The red triangle indicates Tungurahua volcano.

in Hualcanga and Sabañag), and blackberry are sown and harvested throughout the year. Corn, frijole, fava bean, and black seed squash are harvested over a two- to three-month period, beginning between November and February. Fruiting of deciduous fruits takes place around November and the harvest lasts for two to three months between February and April.

3.2 Tephra-induced damage to crops and crop vulnerability to tephra

All farmers interviewed were adamant about tephra fall causing detrimental effects on crop plants, eventually reducing crop production. Leaf yellowing, burning, and drying were noted as the most common visual symptoms appearing after a tephra event (Figure S1 (Supplementary Material)). Tephra also reportedly caused abrasion damage to fruits; in some cases (e.g. tangerine) tephra particles became embedded in the fruit's skin. Black seed squash, corn spikes and greengage, blackberry, peach, and tamarillo fruits tended to rot quickly after tephra deposition (Figure S1; Supplementary Material). Farmers further emphasised that pubescent leaf surfaces typically retained more tephra than glabrous ones. The same observation was made for fruits, with tephra easily adhering to the hairy surface of peach but not to the glabrous skin of tamarillo (Figure S1; Supplementary Material).

Potato, frijole, fava bean, tamarillo, black seed squash, peach, apple, and/or blackberry were reported to be the most sensitive crops to tephra. While Tungurahua's farmers could not rank their crops in terms of vulnerability, they conceded that white onion was most resistant. The flowering stage was unanimously perceived as a period of extremely high vulnerability for any crop. Frijole, fava bean, and black seed squash were also considered to be particularly at risk if tephra fall occurred during fruit growth or fruit ripening, whereas corn was notably sensitive to tephra when grain started forming. When fruit trees reached fruit set, significant damage from tephra could occur, but the fruits became less fragile as they grew (Figure S1; Supplementary Material). Interviewees reported that tree fruits became more resistant to tephra once they had reached approximately half of their final size.

3.3 Crop yield loss and crop abandonment

Farmers experienced a decrease in harvest yield for all types of crops after Tungurahua resumed its eruptive activity in 1999. Incurred losses reached 100 % when the tephra fall event coincided with crop flowering stage. Total loss was also reported when exposure to tephra occurred at fructification stage or when the fruits (e.g. black seed squash, tamarillo, apple, greengage, pear, blackberry, and tangerine) and pods (e.g. frijole and fava bean) had just appeared. Even later when the fruit was at the ripening stage (e.g. tamarillo, apple, greengage, peach, blackberry, and pear), a large reduction in crop yield was observed after tephra

Table 1: Names, altitudes, and distances to the volcano of the 15 villages where the farmer interviews took place, and list of the main and secondary crops cultivated in these localities as in 2014. A map of the village locations is shown in Figure 1.

Village	Altitude (m a.s.l.)	Distance to the volcano (km)	Main crops	Secondary crops
Juive Grande	1990	6.0	corn, tamarillo	frijole, tangerine
Cusúa	2262	6.3	corn, tamarillo	frijole, potato
Bilbao	2296	6.6	corn, frijole, tamarillo	potato, blackberry
Yuibug	2440	6.8	corn, tamarillo	frijole, potato
El Altar	2469	9.9	corn, frijole, potato, apple	pear, peach
Puela	2492	8.8	corn, frijole, potato, tamarillo, apple	peach, greengage
Choglontus	2586	7.0	corn, frijole, potato, tamarillo	fava bean, dark-seed squash, apple, greengage
El Manzano	2586	7.7	corn, frijole, potato	apple, peach, greengage
Cotaló	2599	8.2	corn, frijole, potato	fava bean, apple, greengage
Pillate	2680	8.2	corn, white onion	potato, frijole
San Jose del Chazo	2939	13.9	corn	dark-seed squash, potato
Sabañag	3489	14.9	white onion	potato, fava bean
Hualcanga	3496	16.3	potato, white onion	fava bean
El Santuario	3507	12.9	white onion, potato	fava bean
Santa Fe de Galán	3591	13.9	white onion	potato

deposition. The respondents indicated that potato tubers did not reach their final size if they were exposed to tephra fall at the end of leaf growth.

Figure 3 summarises the perception of crop yield loss between 1999 and 2014 across all surveyed villages. Irrespective of the village location, between 33 and 69 % of farmers consider that their harvest was reduced by 50 %. In ten villages (Juive Grande, Cusúa, Bilbao, Yuilbug, El Altar, Puela, Choglontus, El Manzano, Cotaló, Pillate), between 13 and 67 % of the interviewees claimed losses equal to 75 %. In Juive Grande, Cusúa, Bilbao, El Altar, and Puela, total loss of crop yields affected 5–14 % of the farming community interviewed.

A noticeable finding of the survey is a reduction in crop diversity between 1999 and 2014, as outlined in Table 2. Depending on location, between 30 and 100 % of the respondents reported that they stopped cultivating at least one and up to five crops. The villages most affected are Yuibug, Choglontus, San José del Chazo, and Santa Fe de Galán, where 100 % of the farmers no longer grow blackberry and tomato, blackberry, carrots and pea, pea, fava bean, potato, barley and frijole, fava bean, carrot, barley, and shallot, respectively. Overall, between 1999 and 2014, nine out of the 15 villages abandoned the cultivation of pea, seven villages abandoned fava bean, five villages abandoned barley, four villages abandoned carrot and cabbage, three villages abandoned ullucos, two villages abandoned potato, peach, blackberry, wheat, and shallot and one village abandoned tamarillo, broccoli, pear, black seed squash, squash, frijole, oca, and lettuce. Moreover, the farmers declared that areas devoted to tree fruits (in particular tamarillo, peach, and pear), blackberry, potato, seed squash, and frijole cultivation shrunk in size. White onion was typically grown in replacement of crops that are sensitive to tephra.

3.4 Mitigation measures for tephra impacts

Farmers attempted to reduce the impact of tephra on corn, frijole, potato, fava bean, and onion by shedding the tephra particles off the foliage (Figure S2; Supplementary Material). This was done manually through gentle shaking of the plants, sometimes using a stick. The same treatment was applied to deciduous fruit trees (tamarillo, apple, pear, greengage, and tangerine), but when the tephra deposit was too thick, the farmers tended to rely on wind and rain as erosion agents. They did not attempt to remove tephra from small plants or plants in the flowering development stage as these were believed to be too fragile and the damage irreversible. Fruits, such as apple and tangerine, which had reached their final size could be partially salvaged by manual cleaning, although appearance and taste may have degraded after exposure to tephra. The farmers further indicated that tephra-induced damage to black seed squash, peach, and blackberry could not be prevented, for this reason, these fruits were not tended to if they accumulated tephra.

When water was readily available, hose nozzles and sprinklers were used to wash the tephra off crop leaves

Figure 2: Illustration of the crop calendars for the main crops cultivated in the 15 villages surveyed in 2014. Each-crop specific calendar shows the period of sowing (annual plants), fruit appearance (fruit trees), and harvest. The period corresponding to the plant development stage(s) (i.e. leaf production, flowering, and fruit/grain formation) most vulnerable to tephra fall is indicated in blue.

(Figure S2; Supplementary Material). Fruits ready to be picked were also washed with water, but this technique was inefficient for fruits with a pubescent or rough skin (e.g. peach, tangerine, and blackberry). If tephra fallout affected a product that was almost fully mature, the farmers hastened the harvest. A drastic measure applied by some of the richest growers to protect the blackberry production was the construction of greenhouses. All respondents agreed that the actions taken to minimise the damaging effects of tephra on crops were labour intensive.

3.5 Farmers' observations of tephra characteristics

Farmers at Tungurahua distinguish four types of tephra deposits based on colour and particle size: "white fine," "black coarse," "grey medium," and "red coarse" tephra. The "white fine" and "black coarse" materials were always mentioned in the interviews. Some farmers from Choglontus, El Manzano, El Santuario, Puela, Pillate, Cotaló, Santa Fe de Galán, and El Altar pointed to the occasional "grey medium" tephra deposit. The "red coarse" material was reported infrequently in the villages of El Manzano, El Santuario, El Altar, and Bilbao. The interviewees unanimously emphasised that the "white fine" tephra inflicted the most severe damage to crops. This material readily stuck to plant foliage and fruits, and could not be removed by shaking or even washing. The farmers also insisted that the likelihood of losing at least 50 % of the harvest was high when the tephra deposit corresponded to the "white fine" type.

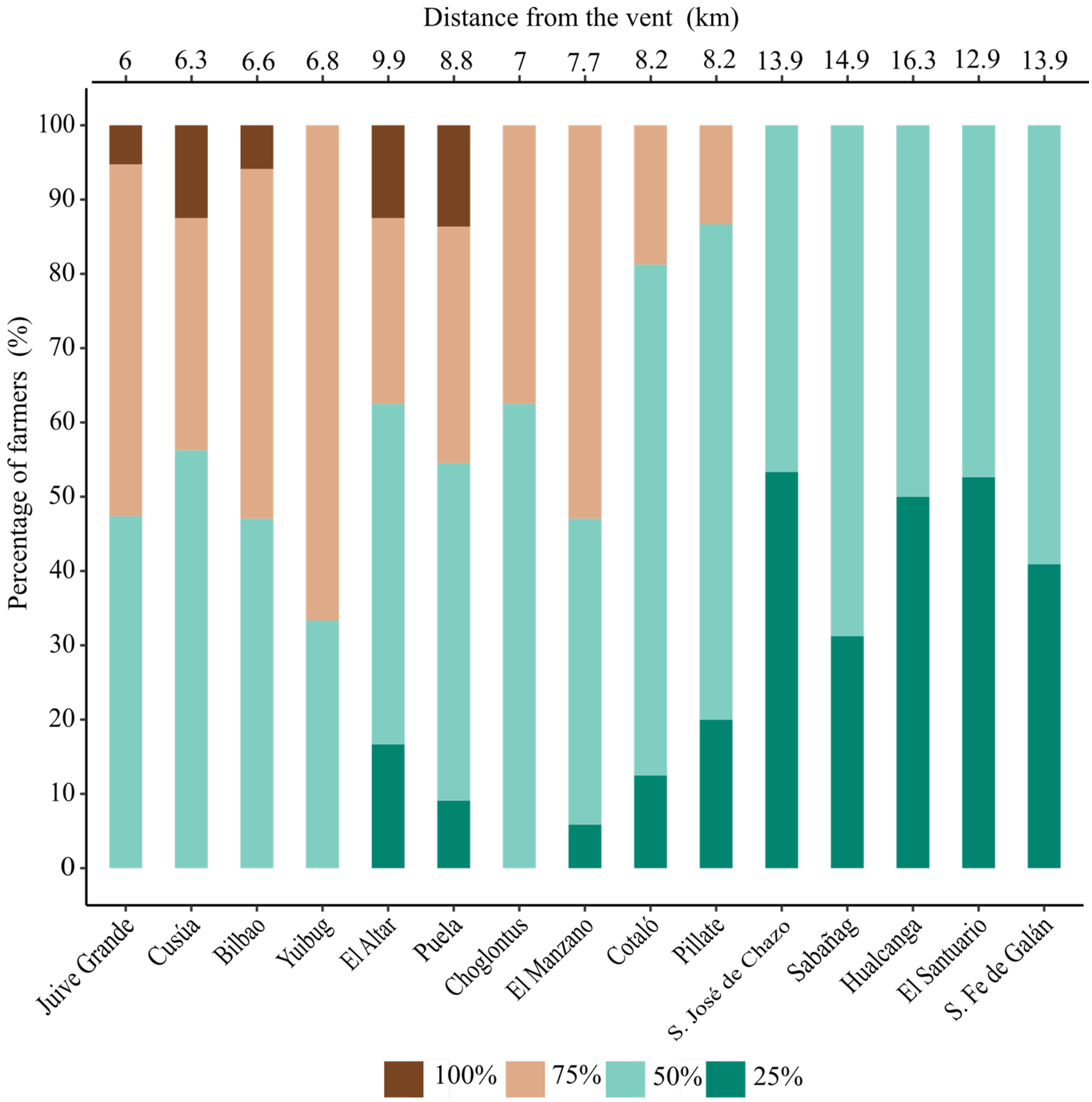

Figure 3: Percentage of farmers in each of the 15 villages surveyed who estimated a crop yield reduction x for the period 1999–2014 of $0 < x < 25$, $25 \leq x < 50$, $50 \leq x < 75$, $75 \leq x < 100$ and 100 %. Distance of the village from the vent is also shown.

4 Discussion

Our survey reveals that recurring tephra fall downwind of Tungurahua volcano in the period 1999–2014 affected crop cultivation significantly. Of the 24 types of crops grown prior to the onset of the eruption in the 15 villages surveyed, 11 were discontinued in 2014, i.e. a ∼50 % reduction in crop diversity. Moreover, among the 13 remaining crops, some were abandoned in at least one village. The crops that are no longer produced (or only in very small quantities for subsistence) include carrot, ulloco, cabbage, barley, wheat, pea, lettuce, broccoli, oca, shallot, and squash. In two villages (Juive Grande and San José del Chazo), cultivation of potato was interrupted. In other localities, the size of the land for growing potato and corn was reduced in order to allow more white onion cultivation. Besides crop abandonment, variable yield losses occurred depending on crop type and village location, indicating that crop vulnerability to tephra varies spatially and temporarily.

4.1 Factors modulating tephra impacts on crops

4.1.1 *Thickness and particle size of the tephra deposit*

The yield loss of all crops combined reported by smallholder farmers varies between 25 and 100 % (Figure 3). The villages situated less than 7.4 km from the volcano (i.e. Juive Grande, Cusúa, Bilbao, Yuibug, Choglontus) endured a loss exceeding 50 %, and 6 % of the farmers claimed a total loss of their harvest. At distances between 7.4 and 9.9 km from Tungurahua (i.e. El Manzano, Cotaló, Pillate, Puela, and El Altar), a maximum yield loss of 100 % was also reported, although 13 % of the farmers declared a loss <25 %. Further away, up to

Table 2: Percentage of farmers in each of the 15 villages surveyed in 2014 who abandoned one or more crop types over the period 1999–2014.

Village	Percentage of farmers who abandoned at least one crop	Crop type abandoned
Juive Grande	60	carrots, potato, ullocos, fava bean, cabbage
Cusúa	30	pea, fava bean, tree tomato
Bilbao	85	fava bean, barley, peach
Yuibug	100	blackberry, tomato
El Altar	50	pea, wheat, barley
Puela	65	barley, fava bean, pear
Choglontus	100	blackberry, carrots, pea
El Manzano	70	cabbage, broccoli, wheat
Cotaló	55	pea, cabbage, black seed squash, peach
Pillate	85	fava bean, squash, lettuce, cabbage, carrot
San Jose del Chazo	100	pea, fava bean, potato, barley, frijole
Sabañag	85	pea, ullocos, oca, shallot
Hualcanga	35	pea
El Santuario	60	pea, ullocos
Santa Fe de Galán	100	Pea, fava, bean, carrot, barley, shallot

16.6 km from the volcano, in the locations of El Santuario, San José Chazo, Santa Fe de Galán, Sabañag, and Hualcanga, the yields shrunk by 25 to 50 % compared to the pre-eruptive period. These results suggest that the detrimental effect of tephra fall on crop yield diminishes with downwind distance from the source. In general, proximal tephra fall deposits are thicker than distal ones, and the evolution of tephra thickness as a function of distance from the volcano is often approximated with an exponential thinning law [Pyle 1989; Bonadonna et al. 1998]. For example, during the July 2006 eruption of Tungurahua, the tephra deposit at Pillate, 8 km west of the volcano, was seven times thicker than at Hualcanga, another 8 km further west [Figure 1; Eychenne et al. 2012]. As already observed in other post-eruption impact assessment studies [Wilson et al. 2007; Jenkins et al. 2015; Craig et al. 2016b; Thompson et al. 2016], our results point to deposit thickness as an important metric for predicting a reduction in crop productivity.

Farmers from Tungurahua systematically referred to the "white fine" tephra type as being the most harmful to crop plants. Tephra colour is influenced by bulk composition, e.g. basalt is dark-coloured, whereas rhyolite is pale-coloured, often grey, tan, or pinkish. Chemical alteration also modulates tephra colour and in particular the oxidation of iron oxides, which produces a brownish colour. Tephra colour can further change with particle size as the increased surface area associated with finer particles enhances light scattering by the tephra. According to previous studies, the tephra emitted between 1999 and 2013 had a basalt-andesite to andesite composition [Samaniego et al. 2011; Myers et al. 2014; Guevara 2015]; therefore, transient changes in bulk chemistry cannot explain the occurrence of "white fine" tephra. The presence of altered lithics is also unlikely to confer a pale colour to the tephra material.

To understand the nature of the so-called "white fine" tephra to which farmers had referred during the interviews, we prepared a chart with six photos of Tungurahua's tephra specimens that differed in their content of fine particles (<63 µm), i.e. <5, 5–10, 10–20, 20–30, 30–40, and >40 weight percentage (wt.%), and hence, colour (Figure 4). These materials were obtained from a suite of 43 samples collected between October 1999 and May 2013 downwind of the volcano (Table S2; Supplementary Material). The wt.% of particles <63 µm in the tephra was estimated by dry-sieving. Fifteen farmers from the villages of El Manzano, Choglontus, and Puela were asked to select the photo in Figure 4 which best represented the material most damaging to crops. In all but one case, they identified tephra containing ≥20 % of fine particles. This observation points to particle size as another important tephra property, besides deposit thickness, that modulates impacts on crops.

4.1.2 *Crop development stage*

According to farmers, crops in the flowering stage were most vulnerable to tephra deposition. A few millimetres of tephra were sufficient to annihilate the harvest. The only exceptions are white onion and potato, for which bulb and tuber formation, respectively, does not require pollination [Jansky and Thompson 1990; Díaz-Pérez et al. 2003; Tekalign and Hammes 2005].

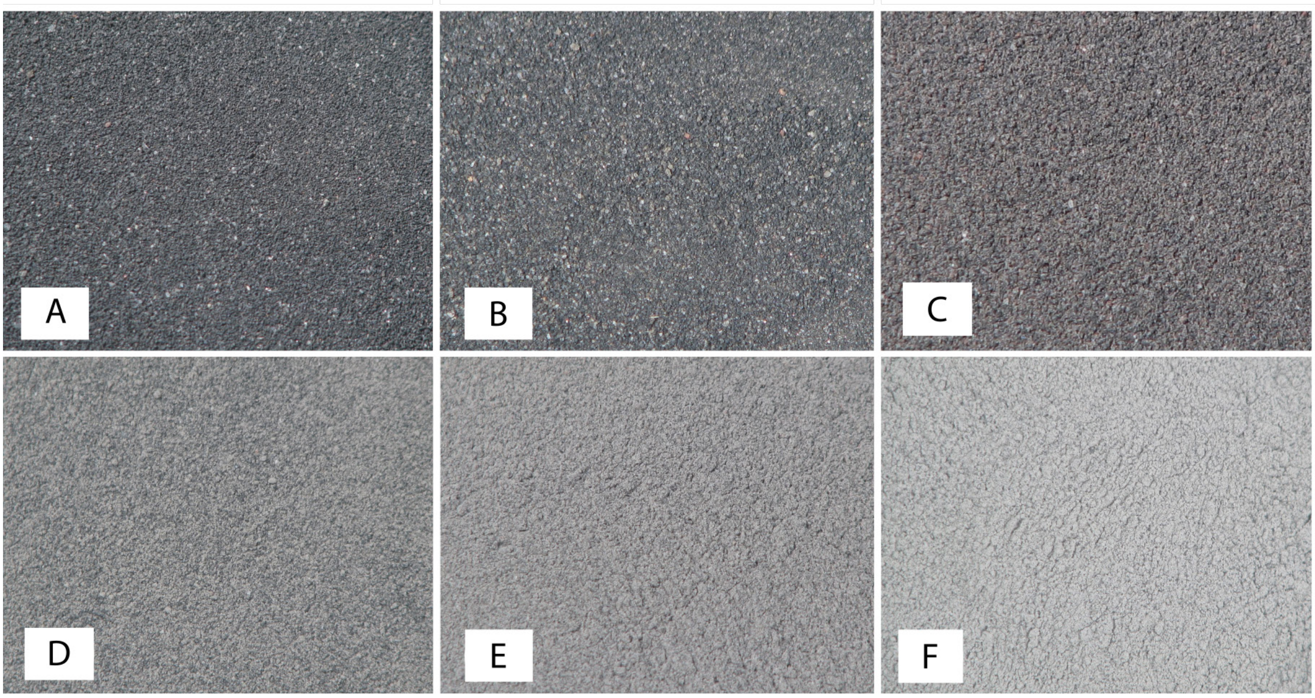

Figure 4: Photographs of six tephra materials erupted by Tungurahua volcano, each being characterised by different <63 μm-particle contents: <5 % [A]; 5 ≤ x < 10 % [B]; 10 ≤ x < 20 % [C], 20 ≤ x < 30 % [D]; 30 ≤ x < 40 % [E]; and ≤ 40 % [F].

For other crops, fruit formation is impeded when pollination and fertilisation are limited or cannot take place due to coverage of the plant's reproductive organs (i.e. stigma and anther) by tephra [Rees 1970]. Previous studies indicate that tephra has an adverse effect on pollinators, likely also contributing to vulnerability at the flowering stage [Cook et al. 1981; Neild et al. 1998; Wilson et al. 2009; 2011]. For crops such as frijole, squash, and some fava bean varieties which produce flowers continuously [Sage and Webster 1987; NeSmith and Hoogenboom 1994; López-Bellido et al. 2005], impact may be limited if the plant remains vigorous enough to produce new flowers after tephra fall. Similarly, flowering was recognised as a period of fruit and vegetable vulnerability to tephra during the 1980 eruption of Mt. St. Helens, USA, and the 1995–1996 eruptions of Mt. Ruapehu, New Zealand [Mack 1981; Neild et al. 1998].

Tephra deposition on plants that already bear fruit is also detrimental to crop yield. Farmers in Tungurahua reported that fruits that had not reached 50 % of their final size were more prone to damage. This is in line with previous observations made for horticultural crops affected by Mt. Ruapehu's tephra falls [Neild et al. 1998]. The aggregate blackberry and pubescent peach fruits were most susceptible to tephra. Such fruit traits seem to favour tephra retention and thus, potentially damage. Enhanced retention of tephra on pubescent leaves (e.g. apple, tobacco, tomato) and pubescent or rough-skinned fruits (e.g. peach, apricot, kiwi-fruits, strawberry, and raspberry) was also noticed after the explosive activity of Mt. St. Helens in 1980 [Cook et al. 1981] and the 2006 eruption of Mt. Merapi, Indonesia [Wilson et al. 2007]. In contrast, the presence of a wax layer on the surface of greengage and tamarillo exerts a protective effect against damage by tephra. Similarly, waxy cabbage leaves may be less prone to tephra damage compared to non-waxy leaves as the former can shed tephra particles readily [Wilson et al. 2007]. However, a fruit such as tangerine or citrus [Wilson et al. 2007] with a waxy but rough skin tends to retain tephra.

Fruits with a hard (and presumably protective) skin may also suffer injuries from tephra, but the mechanism by which these develop is different. According to farmers, squash fruit rotted quickly in the field after exposure to tephra. The symptoms usually developed on the side of the fruit in contact with tephra on the ground. Water retention in a tephra deposit probably leads to high moisture conditions suitable for pathogen growth [Aung et al. 2018; Velásquez et al. 2018]. Miller [1966] and Cook et al. [1981] suggested that, under moist conditions, the dying plant tissue and tephra layer on soil favour the development of fungal pathogens, probably explaining why squash fruits degraded rapidly after a tephra fall.

4.1.3 *Surface area and morphological characteristics of crop leaves*

The potential for tephra to cause damage to crops mainly relates to the ability of the plant's aerial parts to intercept and retain tephra particles. Several surface characteristics (e.g. roughness, hairiness, shape, size, angle) of the leaves favour retention of tephra particles. For example, our survey reveals that tephra is prone to stick to the foliage of fava bean, potato, frijole, and black seed squash. We attribute this mainly to the leaf hairiness or roughness, and the total leaf surface area. Leaf angle, i.e. the inclination between the midrib of the leaf and the vertical stem of the plant, also plays a role, and horizontally orientated leaves (e.g. black seed squash) tend to collect more tephra. Figure 5 illustrates the influence of leaf shape and leaf angle on the retention of tephra on the surface of black seed squash, corn, and onion leaves. The foliage of black seed squash is characterised by large multilobed and horizontal leaves and retains more tephra than that of corn and onion, which both feature linear blade leaves in the upright position.

The retention of tephra on foliage may impact plant development and ultimately crop yield. Non-volcanic dust particles have been shown to reduce the leaf photosynthetic area and hence the amount of light intercepted [Thompson et al. 1984; Hirano et al. 1990; 1991; 1995]. Similarly, the presence of tephra on leaves reduces photosynthesis through leaf shading [Hirano et al. 1992; Tarasenko 2018]. At Tungurahua, the farmers indicated that leaves covered by tephra turned yellow before drying and eventually falling off, and sometimes described this effect as "leaf burning". Similar observations were reported in previous post-eruption impact assessment studies and are often referred to "acid burns" [Miller 1966; Neild et al. 1998; Wilson et al. 2007; 2011]. However, this terminology is misleading as it suggests the chemical action of an acidic substance supposedly released from tephra. While tephra from phreatic and phreatomagmatic eruptions may contain reduced sulphur compounds (i.e. elemental sulphur or sulphide such as pyrite, FeS_2) that may oxidise to sulphuric acid in the presence of water, tephra produced by purely magmatic eruptions rarely carries such compounds and should not produce acid leachates [Delmelle et al. 2021]. This has also been confirmed for Tungurahua's tephra [Guevara 2015]. Thus, crop leaf yellowing and "burning" at Tungurahua probably points to a physical process in relation to leaf coverage by tephra particles.

Leaf yellowing (also known as leaf chlorosis) is a condition in which leaves produce insufficient chlorophyll. Various factors such as nutrient deficiency, water stress, presence of pathogens, contamination by heavy metals, elevated temperatures, and abnormal light intensity may induce chlorosis [Isaac and Adamson 1934; Korcak 1987]. Volcanic ash (tephra <2 mm) applied to cucumber reduces photosynthesis due to shading of the leaf surface, increased leaf temperature, and clogging of stomata [Hirano et al. 1992]. Using non-volcanic dust, Hirano et al. [1990; 1995] argued that shading is the main physical process affecting leaf photosynthesis. These authors also highlighted a stronger shading effect and reduction in light intensity reaching the leaf surface of cucumber and bean plants when smaller particle sizes were applied. Since light intensity modulates the expression of genes involved in chlorophyll synthesis, lower light intensities can decrease the leaf chlorophyll a and b contents, eventually leading to leaf lighting [Wang et al. 2018]. Leaf senescence (i.e. chlorophyll and other macromolecules catabolism leading to leaf death) can also be triggered by leaf shading [Weaver and Amasino 2001; Lim 2003; Brouwer et al. 2012]. Based on these studies, we argue that the shading effect of tephra on crop plants is likely responsible for the discolouration (yellowing), drying, and abscission of leaves systematically reported by farmers at Tungurahua. Since subdued photosynthetic activity often reduces crop yield [Isaac and Adamson 1934; Richards 2000; Sharma-Natu and Ghildiyal 2005; Lawson et al. 2012], diminution in light interception caused by tephra on leaves may explain the smaller than usual sizes of potato tubers and corn grains, and more generally the loss of crop production around Tungurahua volcano (Figure 3).

In order to predict the vulnerability of an agricultural crop to tephra, Bignami et al. [2012] and Craig et al. [2016b] proposed classifications based on the height and edible part(s) (as defined by Arteca [2014]) of the crop plant, respectively. For example, crops are categorised as root vegetables (e.g. potato, carrot, onion), fruiting vegetables (e.g. fava bean, frijole, black seed squash), and tree fruits (e.g. peach, apple, orange). However, this approach may not be adequate because two plants belonging to the same crop group can have contrasting vulnerability due to different plant morphological characteristics. Our results illustrate this in the cases of potato and white onion. Although the two crops belong to the tuber crop category, tephra deposition was reported to impact potato significantly but has a minor effect on white onion. Similarly, tree fruits exhibit different vulnerabilities to tephra depending on skin traits; for example, peach and apple are highly sensitive, whereas greengage and tangerine are much less vulnerable.

4.1.4 *Mitigation measured deployed by the farmers for tephra impacts on crops*

Farmers in Tungurahua had little means to prevent tephra fall from damaging their crops. If manual shaking of plants covered by tephra can remove some of the deposit, it is labour intensive and much less efficient than using water to wash it away. However, the smallholder farmers stressed that the availability of water

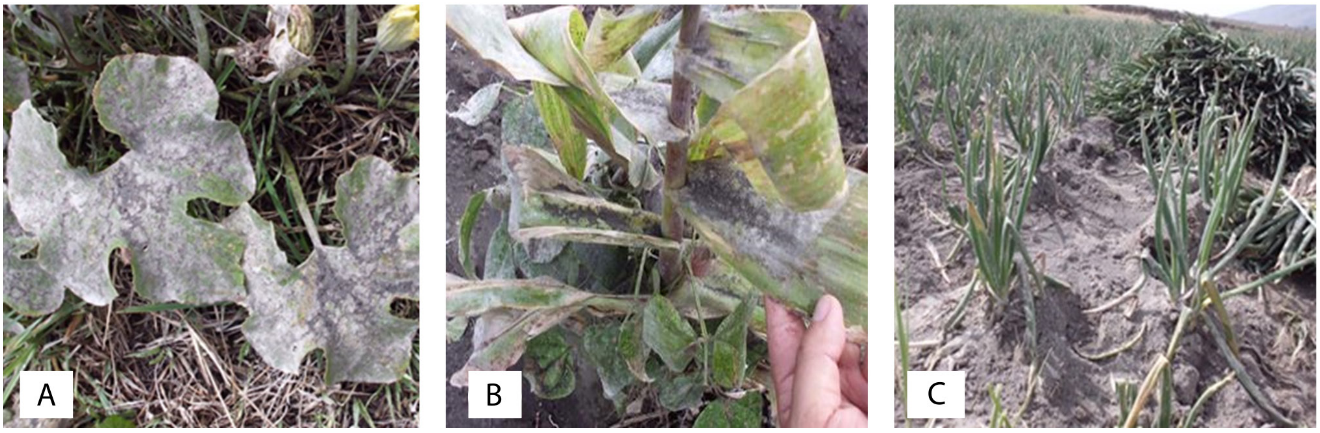

Figure 5: Influence of leaf shape and leaf angle on tephra retention on foliage for three crop plants found in the study area: black seed squash; multilobed and horizontal leaves [A]; corn; linear blades in upright position [B]; white onion; corn; linear blades in the upright position [C].

and water equipment limited their capacity to act soon after an eruption. Wilson et al. [2007] made the same remark for farmers in the agricultural region affected by the 2006 eruption of Mt. Merapi.

4.2 Inferring the spatial and temporal vulnerability of crops to tephra

The analysis of farmer interviews reveals a relationship between the dominance of specific crops and altitude. Using the observations summarised in Table 1, we identify three major zones of cultivation: (i) corn, potato and fruit trees prevail at altitudes of 1900–2600 m a.s.l., (ii) corn and potato coexist at altitudes of ~2600–3000 m a.s.l., and (iii) white onion and potato dominate at altitudes of ~3000–3600 m a.s.l. This distribution of crops agrees with the agricultural zonation typically found in the Andes where altitude dictates temperature and therefore, constrains vegetation [Stadel 1991]. On this basis, and using a digital elevation model of the Tungurahua region, we extended the zonation of crop production inferred from our observations at the village level across the entire study area (Figure 6).

Altitude not only determines the type of crop cultivation but also modulates the yearly cycle of crop planting and harvesting in the Tungurahua area. For example, compared to the villages of Juive Grande (1990 m a.s.l.) and Cusúa (2262 m a.s.l.), the sowing period of corn and frijole is delayed by two to three months in communities situated northwest and southwest of the volcano along the Rio Chambo (i.e. Bilbao (2296 m a.s.l.), Yuibug (2440 m a.s.l.), El Altar (2469 m a.s.l.), Puela (2296 m a.s.l.), Choglontus (2586 m a.s.l.), El Manzano (2586 m a.s.l.)), and in the mountains across the Rio Chambo (Cotaló (2599 m a.s.l.), Pillate (2680 m a.s.l.), and San José del Chazo (2936 m a.s.l.). The discrepancy in the crop cycle between different locations probably relates to variations in the seasonal distribution of rainfall as influenced by altitude. For example, in the Eastern Cordillera (e.g. Juive Grande) the highest rainfall normally occurs in June, whereas in the high-altitude region of the intra-Andean valley (e.g. Pillate and San José del Chazo), October and June–August coincide with the maximum rainfall periods, whereas March-April are the months with minimum rainfall [Laraque et al. 2007]. Precipitation in the Ecuadorian Andes tends to increase on the lower slopes and decrease above 2500 m a.s.l., but a simple relationship between altitude and rainfall is difficult to establish as the steep topography and associated terrain complexity lead to strong spatial rainfall variability.

Since the vulnerability of crop plants to tephra depends on growth stage, the basic crop-specific calendars constructed from the interviews (Figure 2) can be used to find the time windows during which a tephra fall is more likely to be harmful to a specific crop. Accordingly, crops sown and harvested all year round (i.e. potato, fava bean, tamarillo, and blackberry) will always be vulnerable to tephra fallout. Most tree fruit crops will be more vulnerable between November and December and between January and March. For tangerine, the critical months are March, May, June, September, November, and December. Corn and frijole reach the flowering stage between June and November, depending on location, and will be vulnerable to tephra exposure until the grains or pods have formed, i.e. two months after flowering. For fava bean (cultivated in Choglontus, Cotaló, and El Santuario) and black seed squash, the period of vulnerability starts in August (one month after sowing) and lasts until December.

Knowing the spatial distribution of a given crop in the study area and its altitude-dependent cultivation cycle, we can outline how its vulnerability to tephra varies throughout the year. Figure 7A shows the temporal vulnerability map obtained for tree fruits (apple, greengage, peach, and pear). After harvest, apple, greengage, peach, and pear trees in El Altar, El Manzano, Puela, Cotaló, and Choglontus enter a five-

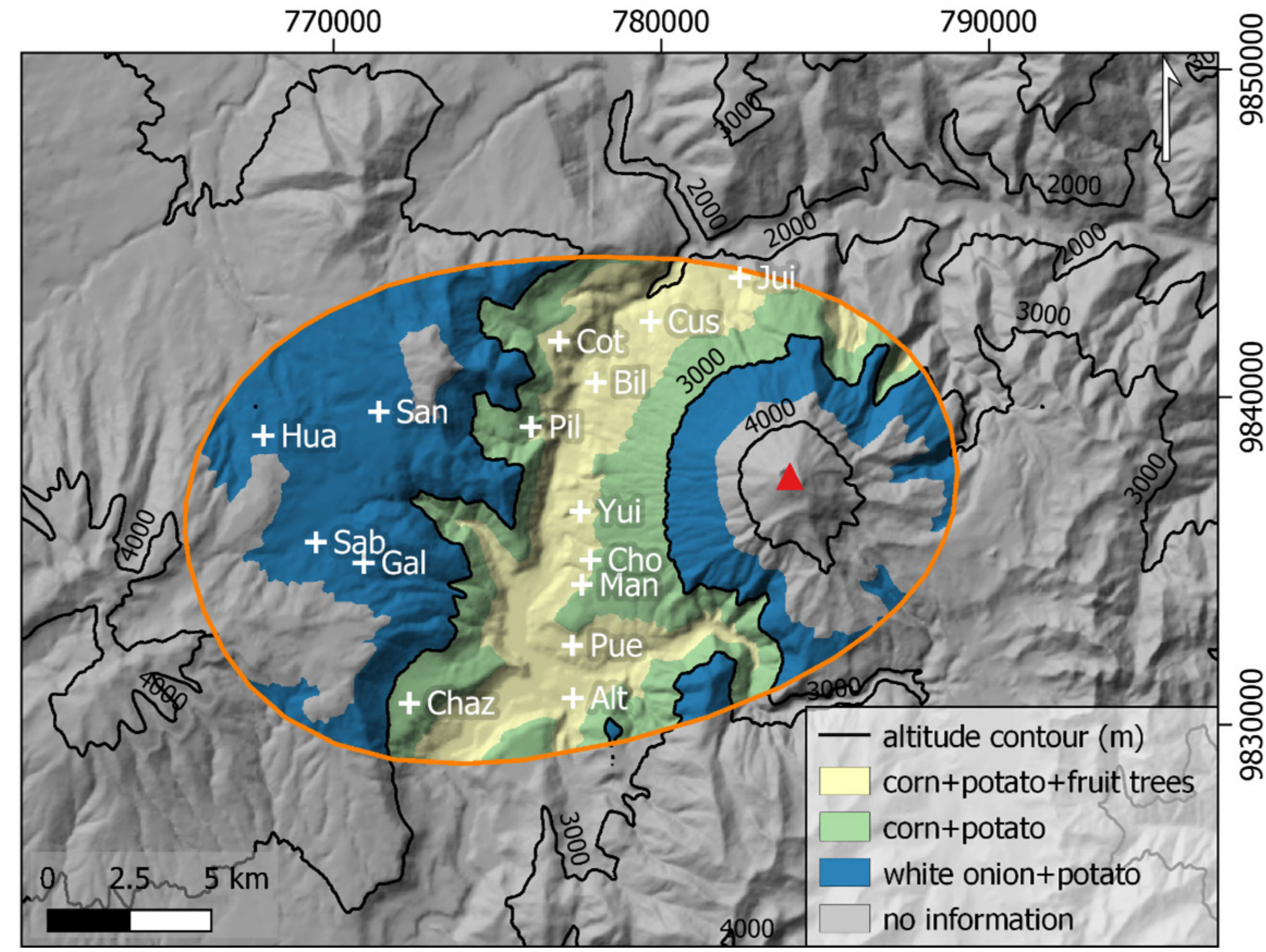

Figure 6: Zonation of crops within the surveyed area (delineated by the orange line). Three zones that differ by the main crop association are distinguished based on altitude: corn+potato+fruit trees, corn+potato, and white onion+potato at altitudes of ~1900–2600, ~2600–3000, and ~3000–3600 m a.s.l., respectively. There is no information for terrains situated at altitudes >3600 m a.s.l. Symbols and village names as in Figure 1.

month period dormancy, usually from April/May to August. A tephra event occurring during this period will have little, if any, impact on tree fruit production, except in the rare case where the tephra load would be high enough to cause mechanical breakage of branches. The months during which most damages are expected are from September to March, when trees are flowering and fruits start forming. Similarly, the temporal vulnerability maps for corn suggests that this crop will be most vulnerable to tephra fall in July–September in Juive Grande and Cusúa; September–November in Bilbao, Yuilbug, Choglontus, El Manzano, Puela, and Cotaló; and October–December in Pillate and San José del Chazo (Figure 7B).

Based on the crop-specific calendars, corn in El Altar would be anticipated to suffer more damage if tephra deposition occurs between September and November. However, the farmers' interviews indicate that the crop cycle in El Altar is delayed by one month, probably due to drier conditions at this location. As a result, corn in El Altar is more vulnerable to tephra in October–December. Applying the same approach, temporal vulnerability maps can be produced for the other main crops (including frijole, black seed squash, potato, white onion, fava bean, tamarillo, blackberry, and tangerine) cultivated in the Tungurahua region.

4.3 Implications for assessing tephra hazard to crops, risk reduction, and future studies

We have shown that the combination of simple knowledge on land use and crop growth provides invaluable understanding of the spatial and temporal variability in crop vulnerability to tephra fallout. Land use in any volcanic regions can be obtained through local surveys or/and via Earth observation data [Giri 2012], whereas crop calendars are usually available from international and national agricultural institutions [FAO 2022; USDA and IPAD 2022]. We suggest that a description of crop vulnerability could be relatively easily embodied within volcanic hazard assessments where

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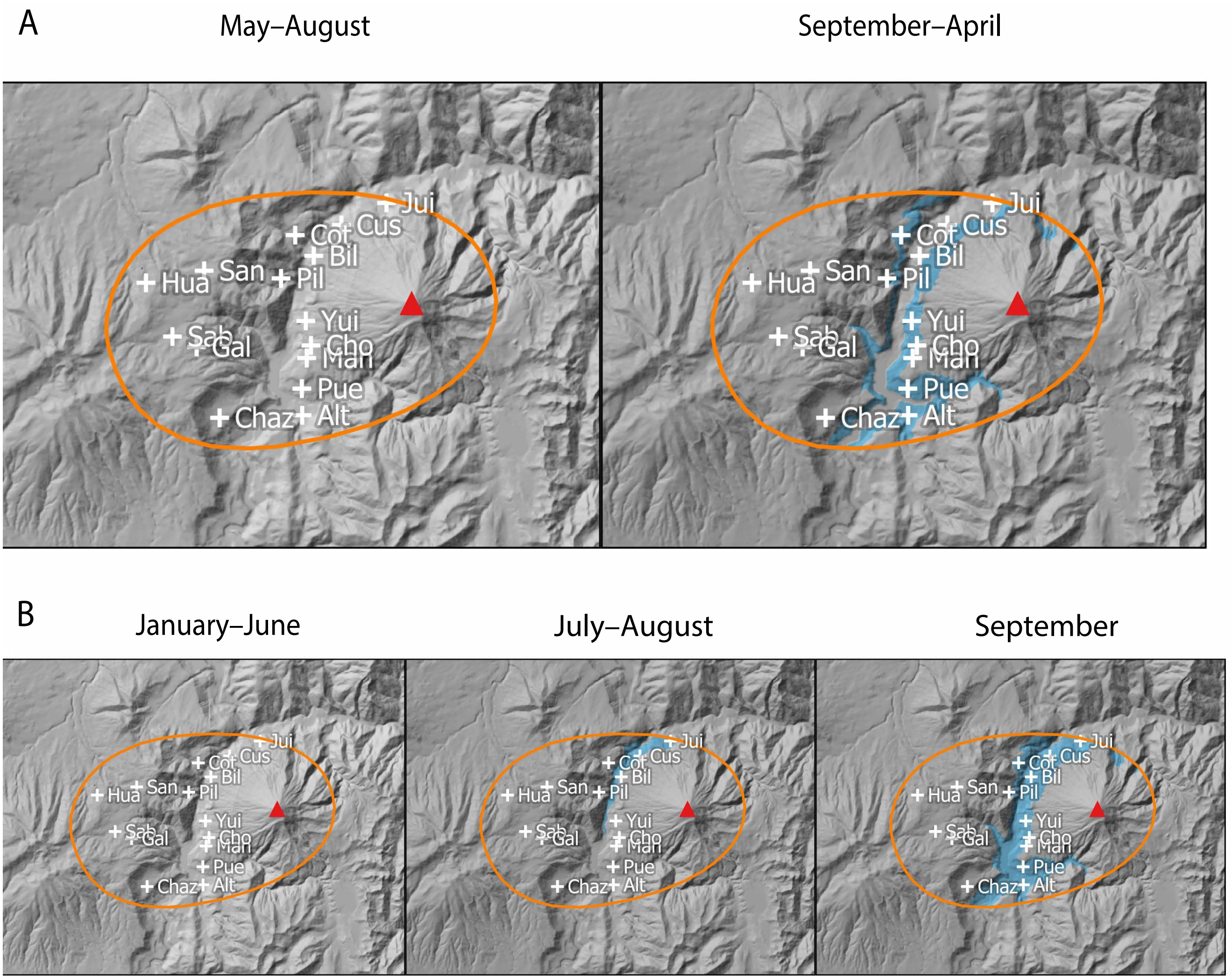

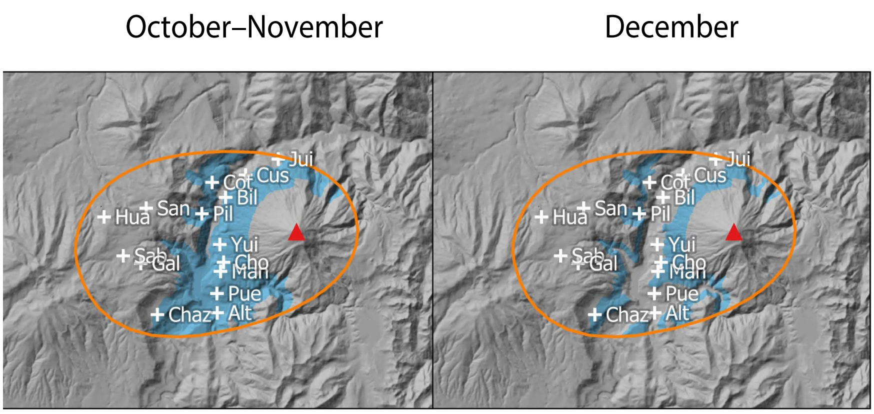

Figure 7: Maps illustrating the spatial variation in crop vulnerability to tephra throughout the year within the surveyed area (delineated by the orange line): fruit trees (e.g. apple, greengage, peach, and pear) [A] and corn [B]. The area across which the crop is vulnerable to tephra is coloured in blue. See text for explanations. Symbols and village names as in Figure 1.

zone maps are used as a basis for formulating flexible measures (i.e. prevention, preparedness, and emergency response) that can reduce the level of risk posed by future eruptions. As an illustration, when fields cultivated with perennial crops coincide with areas prone to heavy tephra deposition, a high vulnerability situation may be anticipated because destruction of this type of crop will entail a long recovery process. Mapping crop calendars across a given area would also allow for timely recommendations on how to best mitigate impacts during or immediately after an eruption. For example, annual crops in the flowering stage which are exposed to tephra should be abandoned as the resources deployed for cleaning plants will not likely salvage the harvest. Instead, rapid reseeding in these areas should be encouraged. In other locations where crop plants have already gone through fructification, using manual labour to swiftly remove tephra from foliage and fruits may help to limit yield losses. Finally, diversification of crops should be encouraged as a risk management strategy because higher crop diversity can lessen impacts from tephra and increase resilience.

The novel findings of our study emphasise the usefulness of situation- and context-specific post-eruption impact assessments to better understand the factors driving crop vulnerability to tephra hazard. A standardised and straightforward methodological framework for primary data collection would facilitate comparison between studies. Craig [2015] proposed a list of items that should be documented in any surveys aimed at evaluating tephra impacts on agriculture. This could be used to develop a standardised methodology. We recommend the adoption of structured questionnaires rather than semi-structured interviews, which are generally harder to prepare, execute, and process.

4.4 Limitations of the study

This study has some limitations. The 15 villages surveyed were selected purposively based on the premise that agriculture at these locations was exposed to ashfall from Tungurahua volcano. Accessibility was an important criterion for selecting the villages. However, in doing so, we excluded remote rural farming communities for which isolation could have created additional drivers of crop vulnerability which would have remained unnoticed.

The second limitation relates to soil fertility and nutrient management. These factors, which are direct determinants of crop yield and quality, likely varied across the surveyed area and thus may partly modulate the impact of tephra on crop yield. Accounting for the effect of soil fertility and nutrient status on crop production loss in response to tephra deposition would necessitate careful soil analyses and description of fertilisation practices. While this is achievable at the farm scale, it becomes impractical in post-eruption impact assessment studies that are deployed over tens to hundreds of square kilometres of cultivated lands.

Another limitation of our survey relates to the complex socio-economic and cultural factors, for example, gender, age, education, religious affiliation, place attachment, and personal experiences, which can influence how individuals perceive risks and impacts from tephra. Farmers develop a complicated relationship with their land, and the environment and their occupation shape their identity and behaviour [e.g. Rhoades 1985; Oudwater and Martin 2003]. Entering the farmer's world is not necessarily easy and a rapport with farmers can be difficult to establish. These dimensions may produce uncertain answers and introduce biases and oversimplifications into the results.

Finally, the data we gathered by interviewing farmers are largely qualitative, and statistics were intentionally confined to the percent of respondents answering a particular question. It could be informative to obtain and review relevant production estimates for the surveyed area from research stations and government offices, and compare these with farmers' perceptions of yield loss during the volcanic crisis. However, a preliminary inquiry revealed a mismatch between the spatial (province level) and temporal (yearly) resolution at which such data are available and that corresponding to our study design.

5 Conclusions

Tephra fall from the 1999–2014 eruptions of Tungurahua volcano repeatedly affected cultivation over a ~300 km^2 area. Interviews with farmers revealed the detrimental effects of tephra on crops, ranging from leaf yellowing and abrasion damage to fruits to total loss of the harvest. Potato, frijole, fava bean, tamarillo, black seed squash, peach, apple, and blackberry were most vulnerable to these effects. As a result, farmers abandoned several crops and often replaced them with white onion, a crop plant little affected by tephra. This practice probably contributed to helping farmers economically during the volcanic crisis. However, it also results in less crop diversity, possibly setting the stage for an agriculture that is more vulnerable and less resilient to external changes and pressures associated with future volcanic and non-volcanic (e.g. severe drought, pest disease) events [Matson et al. 1997; Altieri 1999].

Our study has shed new light on the volcanic and non-volcanic factors that drive crop impacts from tephra fallout. Tephra deposit thickness is an important hazard intensity metric, but tephra grain size also plays a major role. At Tungurahua, we infer that the potential of tephra fall to elicit damage to crops increases when tephra contains several wt.% of fine particles (<63 µm). Tephra-damage to crops from tephra is also strongly dictated by crop characteristics, including the plant life cycle and leaf and fruit traits. Farmers systematically point to flowering as the crop growth stage most vulnerable to tephra impact. In addition, leaf surface area, texture (hairiness and roughness), shape, and angle all influence tephra retention on crop foliage. Tephra on leaves likely decreases photosynthetic activity through a shading effect. For tephra exposure that does not generate direct mechanical damage, perturbation of photosynthesis is probably the primary mechanism responsible for reduced crop production. By establishing crop-specific calendars, we were able to represent the spatial and temporal vulnerability of various crops in the high-risk zone of tephra fall from Tungurahua. We believe that this approach, which is relatively simple to deploy, can augment our capacity to assess tephra hazards and complement volcanic risk analysis and zonation.

A limitation of our results arises from uncertainty in evaluating the influence of socio-economic factors and cultural setting on farmers' perception of tephra-induced impact on and risk for agriculture. Analysing and understanding these more intangible drivers would require new investigations. An additional difficulty relates to obtaining quantitative data on crop damage and loss from interviews carried out several months or even years after an eruption. The relatively low frequency of eruptions also impedes the acquisition of such information. Nevertheless, our study proves that post-eruption impact surveys can shed light on the complexity of crop vulnerability to tephra fallout. This is not only valuable on its own, but it can also underpin the design of controlled experiments aimed at quantifying impact mechanisms of tephra on crop plants. This type of measurements is needed for constructing robust relationships that can predict crop yield loss as a function of tephra hazard intensity. Effort to combine field observations with experimental approaches will improve our capacity to develop reliable risk models for tephra-induced damage to agriculture.

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DATA AVAILABILITY

Aggregated summaries of the interview data are available on request from the corresponding author, PD. The data are not publicly available as they contain information that could compromise the privacy of research participants. Survey information and supplementary data are available alongside this article online as Supplementary Material.

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