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RESEARCH ARTICLE

A quantitative assessment of crop vulnerability to tephra hazard at Tungurahua volcano, Ecuador: understanding the effect of volcanic and biological factors

Noa Ligot[1] · William Viera[2] · Diego Peñaherrera[2] · Benjamin Bernard[3] · Patrick Bogaert[1] · Pierre Delmelle[1]

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Abstract
Crops are regularly impacted by tephra from explosive volcanic eruptions, causing significant economic losses and jeopardising farmers' livelihood at the local to regional scales. Crop vulnerability to tephra remains poorly understood, impeding the construction of robust risk models for agriculture. Previous studies of crop vulnerability to tephra are semi-quantitative and consider tephra accumulation as the only hazard intensity metric. Here, we provide a robust evaluation of crop vulnerability based on the analysis of 700 sets of quantitative data, allowing for the assessment of the influence of various volcanic and non-volcanic factors. We collected farmers' perceptions of damage to fodders, root and tuber crops, leafy crops, legumes, cereals, tree fruits, non-tree fruits, and estimations of their yield loss due to the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptions of Tungurahua volcano, Ecuador. Crop yield loss increased with tephra loads (48 ± 35, 69 ± 33, and 76 ± 34% for <0.5, 0.5–5, and 5–50 kg m^{-2}, respectively), and we found that exposure to tephra led to a greater decline in yield compared to existing predictions. The results further highlight the plant phenological stage as a key factor of vulnerability. Exposure to tephra during the flowering period of legumes, cereals, and tree fruits caused a median yield loss ≥ 80%. Legumes, tree fruits, and non-tree fruits are more vulnerable to tephra than onions. Quantitative knowledge on crop vulnerability to tephra can be obtained from post-eruption impact assessments provided that a large population sample is collected and careful uncertainty analysis is conducted.

Keywords Tephra fall · Agriculture · Impact assessment · Vulnerability · Vulnerability function

Introduction

Agriculture is a critical economic sector in most volcanic regions, with many relying on the high fertility of soils formed from tephra deposits emplaced by explosive eruptions (Shoji et al. 1993; Dahlgren et al. 2004). Rural communities in these areas often derive their main incomes from cultivation of various crops and fodders for animals, but living near explosive volcanoes poses significant risks to livelihoods (Blong 1984). Volcanic eruptions release tephra that can travel long distances on prevailing winds, blanketing hundreds to thousands of square kilometres with deposits of varying thicknesses (e.g., Walker 1973; Eychenne et al. 2012; Houghton and Carey 2015). Tephra fallout can cause temporary damage or complete destruction of croplands, sometimes resulting in compromised harvests for several seasons due to remobilisation of tephra deposits by wind (Martin et al. 2009; Wilson et al. 2011, 2013) and fertile soil burial by a thick tephra deposit (Chaopricha and Marín-Spiotta 2014). While the greatest impacts on crops are generally observed in proximal areas where tephra accumulation is thickest (Blong 1984; Antos and Zobel 1985), significant damage can occur at distal sites, potentially threatening crop yields across wide agricultural lands. Effective natural hazard management relies on predicting disaster damage through a comprehensive assessment of the vulnerability of exposed

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✉ Noa Ligot
noa.ligot@uclouvain.be

1 Environmental Sciences, Earth and Life Institute, UCLouvain, Louvain-La-Neuve, Belgium

2 Instituto Nacional de Investigaciones Agropecuarias, Quito, Ecuador

3 Instituto Geofísico, Escuela Politécnica Nacional, Quito, Ecuador

assets and systems. However, our current knowledge of crop vulnerability to tephra—a major volcanic hazard—remains fragmented, hindering the development of disaster risk reduction strategies necessary for the sustainable development of agrarian systems in volcanically active regions (UNDRO 1980; Jenkins et al. 2015). Most of our understanding of crop vulnerability to tephra comes from field investigations carried out after volcanic eruptions, commonly known as post-eruption impact assessments (post-EIA) (e.g., Wilson et al. 2007; Magill et al. 2013; Blake et al. 2015; Craig et al. 2016b). However, these opportunistic studies are mainly qualitative in nature and not guided by a standardised method. Despite the recent recognition of tephra impacts on crops, the topic has not received the attention it deserves. Studying how tephra affects crops is challenging due to the unpredictable and dangerous nature of volcanic hazards. Moreover, the erodibility of tephra deposits limits the ability to relate key tephra properties (mass load, grain size, and surface composition) to the level of impact.

Current fragility functions link tephra mass load to crop yield loss for various agricultural types such as non-tree fruits/fruiting crops, tree fruits/tree crops, leafy vegetables, cereals, root vegetables, viticulture and paddy (Wilson and Kaye 2007; Craig et al. 2021). However, these relationships are derived from small datasets, usually with less than 20 data points per model, and are valid for one agricultural type. Their associated uncertainties are also not well quantified, which can lead to significant biases in predictions. While other volcanic and non-volcanic factors, including tephra grain size and surface composition, environmental conditions, plant traits, and crop phenological stage, have been identified as potential control factors on crop yield loss (Ayris and Delmelle 2012; Wilson et al. 2015; Ligot et al. 2022; Ligot et al. 2023a, b), their effects have not been adequately quantified. This may reflect a lack of observational data, the absence of a standardised protocol for collecting relevant information in post-EIA studies, and incomplete description of tephra fallout properties, where tephra thickness is usually the only hazard intensity metric reported.

In this study, we utilised 700 sets of quantitative data on crop yields to investigate the effects of volcanic and non-volcanic factors on crop production loss caused by tephra fallout in a ~ 800 km^2 area near Tungurahua volcano, Ecuador. The data were obtained through face-to-face interviews of Tungurahua's farmers. We examined the impacts of tephra on crops during three explosive eruptive periods of the volcano, specifically August 16–17, 2006, October–November, 2015, and February–March, 2016. Tephra distribution data from these events provided insight into various tephra accumulations on the ground and facilitated the creation of an impact dataset covering a wide range of mass loads.

Study site and methods

Tungurahua volcano: geological and geographical background

The Tungurahua stratovolcano, culminating at 5023 m a.s.l., is situated on the Eastern Cordillera of Ecuador (Fig. 1a). It is one of the most active volcanoes in the Northern Andes (Hall et al. 1999; Le Pennec et al. 2008; Eychenne et al. 2012) and its historical explosive eruptions (volcanic explosivity index (*VEI*) of 2–4) were typically accompanied by tephra fall (Le Pennec et al. 2008; Samaniego et al. 2011; Hall et al. 2015).

The area surrounding Tungurahua volcano is characterised by a thriving agricultural sector (FAO 2010). The majority of farms in the region are small in size, typically less than 5 ha, and involved in mixed crop production and livestock raising for milk and beef (Sword-Daniels et al. 2011). The agricultural lands span elevations ranging from ~ 1500 to 4000 m a.s.l. (Fig. 1a), resulting in diverse microclimates depending on location. The valleys exhibit mild temperatures and abundant rainfall, while higher elevations are marked by colder, drier, and windier conditions (INHAMI 2022). The combination of fertile volcanic soils and varying local climates allows for the cultivation of a wide range of crops, including tree fruits, short-cycle crops, and annual crops (Sword-Daniels et al. 2011).

After an 80-year pause, Tungurahua reawakened in late 1999, undergoing alternating phases of quiescence and explosive activity until March, 2016 (Vlastélic et al. 2023). The eruptions produced tephra fallout that usually affected the western and southwestern sectors of the volcano (Eychenne et al. 2012; Bernard et al. 2013; Eychenne et al. 2013; Parra et al. 2016), leading to recurrent damage to agriculture, including crops and livestock. For instance, tephra from the August 16–17, 2006, eruptive period caused US$26,000,000 worth of damage in this region (FAO 2010). Despite some temporary evacuations in September, 1999, August, 2006, and February, 2008, farming activities continued during the 17 years of volcanic activity (Mothes et al. 2015).

Tephra characteristics of the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods

We conducted a field study to investigate the impact of tephra fall on crops during three explosive eruptive periods: August, 16–17, 2006, October–November, 2015 and February–March, 2016. The 2006 event generated a 16- to 18-km-high eruption column and resulted in tephra

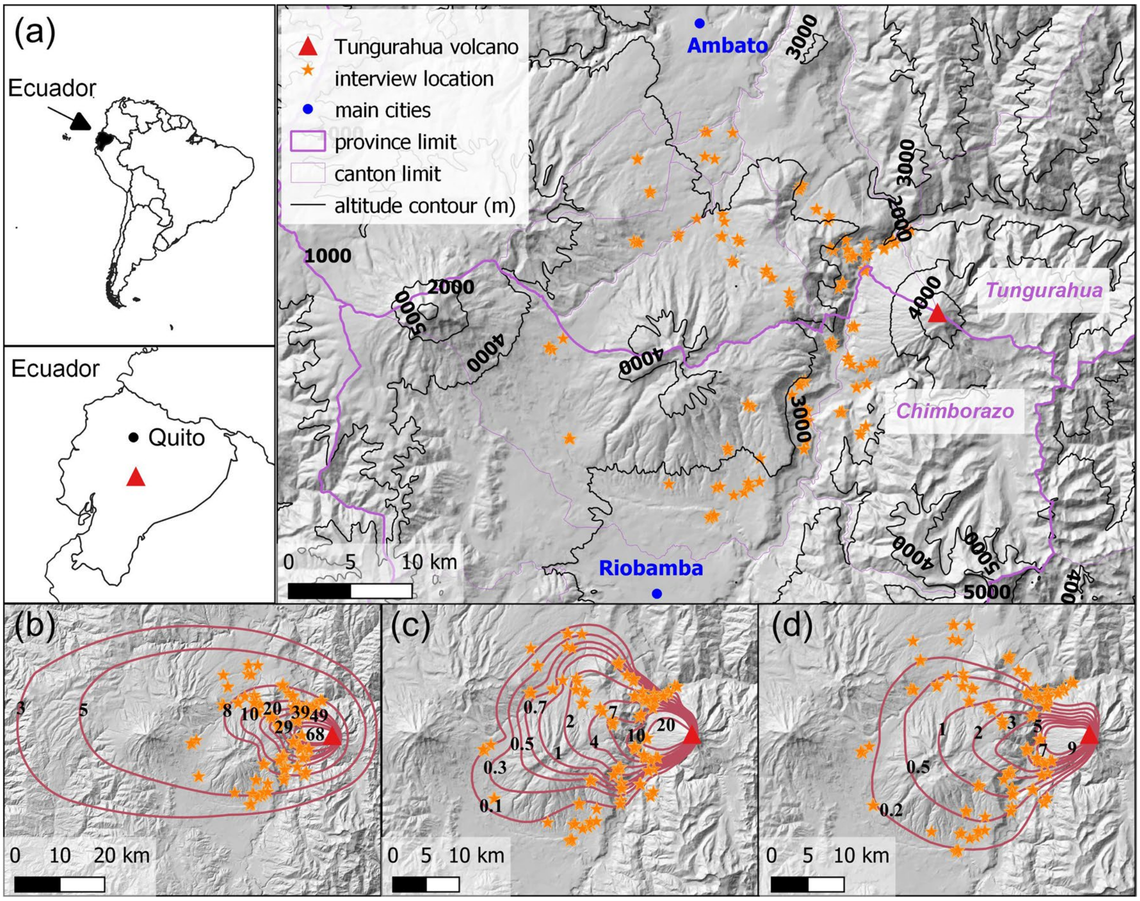

Fig. 1 Map with an inset showing the location of Tungurahua volcano (red triangle) in Ecuador (**a**). Tephra isomass maps in kg m.$^{-2}$ of the August 16–17, 2006, eruptive period (Eychenne et al. 2012) (**b**), October–November, 2015, eruptive period (Vasconez et al. 2021) (**c**), and February–March, 2016, eruptive period (Bernard et al. 2016) (**d**)

deposition over a 3000-km^2 area, extending westward over the Inter-Andean Valley up to the Pacific Ocean (Steffke et al. 2010; Eychenne et al. 2012). This eruptive pulse, characterised by a VEI of 3, was the most powerful of the 1999–2016 period. Approximately 3200 people were evacuated before the explosion (GVP 2006; IG 2006b). The October–November, 2015, activity resumed a 2-month period with relatively small tephra fall (IGEPN 2015). It comprised repeated explosions and sustained tephra emissions over 6 weeks, affecting an area of ~ 650 km^2 (GVP 2017; 2018; Vasconez et al. 2021). The last episode of Tungurahua's eruption occurred between February 26 to March 16, 2016, and produced multiple eruption plumes rising between 3 and 8 km above the crater, covering a ground surface area of ~ 600 km^2 (Bernard et al. 2017).

Tephra accumulations on the ground were obtained for the October–November, 2015, and February–March, 2016, eruptive periods using available isomass datasets (Bernard et al. 2017; Vasconez et al. 2021). For the August 16–17, 2006, eruptive event (Fig. 1b, c and d), we utilised the average deposit bulk density (978 ± 171 kg m^{-3}, $n = 22$ (Eychenne et al. 2012)) to convert the isopach maps into isomass maps. The tephra grain size distribution (GSD) of the 2006 tephra was reported by Eychenne et al. (2012). Samples of tephra from the October–November, 2015 (spatial and temporal series), and February–March, 2016, eruptive periods were provided by the Instituto Geofíso of the Escuela Politécnica Nacional, Ecuador (Fig. S1). To determine their GSD, we utilised both dry mechanical sieving and laser diffraction techniques (Table S1). The 2006 tephra contained coarser particles (> 500 μm) than the tephra from the 2015 and 2016 eruptive periods (Fig. S2). During the 1999–2016 eruptive activity, the magma composition of Tungurahua was primarily andesitic (Hall et al. 1999; Hall and Mothes 2008; Samaniego et al. 2008; Vlastélic et al. 2023). The surface composition of tephra specimens was analysed by Guevara (2015) and revealed low concentrations of anions and cations in the leachate, which is typical of purely magmatic eruptions (Ayris and Delmelle 2012).

Field survey

In August, 2019, we conducted interviews with farmers from Tungurahua to gather knowledge on their farming practices and their exposure to tephra. Our survey consisted of two parts: the first part aimed to obtain general information about the farmer's farm structure, main crops, and crop-specific calendars, whereas the second part focused specifically on their experiences with tephra fall. We sought to collect the farmers' perceptions on how tephra impacted their open-air crops on the short term (less than 1 year), including visual damage, yield loss, and effects of climatic factors like wind and rain on tephra retention on plants. We were also interested in knowing more about the coping strategies the farmers used during and after a tephra fall event.

To collect data, we used a structured questionnaire, a method commonly adopted in risk and impact perception studies related to natural hazards (Gregg et al. 2004; Rego et al. 2018; Shen et al. 2020). The questionnaire was designed with the ODK Collect software and a digital version (Ligot and Garcia 2022) was uploaded on a tablet or a smartphone, to conduct face-to-face interviews with the farmers. The questions were organised thematically (Lohr et al. 2009) and the questionnaire format enables to capture any additional information provided by farmers during the interviews.

We conducted our interviews with farmers within a ~ 800 km^2 area west of Tungurahua volcano. This area received tephra fallout from the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods, and was delimited based on tephra deposit distributions (Fig. 1b, c and d). To ensure a representative sample, we randomly selected interview sites along the road and gravel track network, with the aim of collecting 30–50 interviews in each tephra mass load range (< 0.19, 0.2–0.49, 0.5–0.99, 1–2.99, 3–4.99, 5–7.99, 8–14.99, and 15–50 kg m^{-2}, Table 1), depending on accessibility.

During the interviews, we asked farmers about the main crops grown during the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods. This generated data for various crops at each interview location. The tephra mass load within the surveyed area varied for each of the three eruptive periods: 3–50 kg m^{-2} for August 16–17, 2006, < 0.01–20 kg m^{-2} for October–November, 2015, and < 0.02–7 kg m^{-2} for February–March 2016 (Eychenne et al. 2012; Bernard et al. 2017; Vasconez et al. 2021). In total, we interrogated 123 farmers, generating 123, 112, and 107 impact datasets for the 2006, 2015, and 2016 eruptive periods, respectively.

The interviews were conducted in Spanish with the assistance of agronomists from the Instituto Nacional de Investigaciones Agropecuarias (INIAP, Ecuador) who received training before going to the field. Prior to the interviews, farmers were informed about the purpose of the research and the interview procedures. Their consent was also obtained, which aided to establish trust and improve the quality of the information gathered. Of the 123 respondents, 60% were women and the remainder were men. The age of the respondents ranged from 18 to over 80 years old, and a significant proportion (70%) had not received secondary school education (Fig. S3).

Table 1 The number of farmer interviews corresponding to each tephra mass load range (< 0.19, 0.2–0.49, 05–0.99, 1–2.99, 3–4.99, 5–7.99, 8–14.99, 15–50 kg m^{-2}) as determined based on the interview location and the isomass maps for the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods of Tungurahua volcano (Fig. 1). In total, 342 interviews (one interview for each eruptive phase studied) were carried out with 123 respondents

Tephra mass load range (kg m^{-2})	Number of farmer interviews		
	August 16–17, 2006	October–November, 2015	February–March, 2016
< 0.19	0	38	35
0.2–0.49	0	8	22
0.5–0.99	0	14	21
1–2.99	14	26	19
3–4.99	37	13	7
5–7.99	24	8	3
8–14.99	15	4	0
15–50	33	1	0

The interviewees typically manage small-scale farms (< 5 ha) and depend on family labour to grow crops, such as vegetables, cereals, legumes, and fruits, in open air (Fig. S3). They mainly own the land and use irrigation rarely, relying on the rainy season occurring in October and between March and April (Laraque et al. 2007) for sowing and planting. Livestock, such as cattle, sheep, guinea pigs, pigs, poultry, rabbits, goats, and donkeys, are commonly present on the farm. Most of the farmers in the surveyed area are poor as their family income is often below the minimum Ecuadorian wage (i.e., US$394, CuencaHighLife 2019) (Fig. S3). To supplement their household income, a family member often works in the city (Armijos and Few 2015). Only a few respondents belonged to a farmers' organisation (Fig. S3).

Data treatment and analysis

We analysed tephra fallout characteristics (mass load and GSD), as well as farmers' perceptions of the tephra hazard, including tephra fall duration, residence time on crops, deposit thickness, colour, odour, and grain size, for the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods separately. General information on crop management, such as crop-specific calendars and use of fertilisers and pesticides, were processed by crop type, for instance, potato, corn, etc.

To evaluate the impacts of tephra on crops and crop yields, crops were categorised into seven groups based on the general appearance at maturity and the plant's edible part, following the classification of Bignami et al. (2012) and Craig et al. (2021). The crop groups include fodders, root, and tuber crops (beetroot, carrot, melloco, potato, radish, red onion, white carrot, and white onion), leafy crops (broccoli, cabbage, Chinese cabbage, coriander, lettuce, squash, and Swiss chard), legumes (Andean lupine, frijol, fava bean, and pea), cereals (barley and corn), tree fruits (apple, avocado, capuli, granadilla, lemon tree, peach, pear, plum, tangerine, tree tomato, and dragon fruit), and non-tree fruits (blackberry and strawberry) (Table S2).

To elucidate the factors contributing to the variability in crop yield loss estimates reported in the interviews, we conducted an analysis that considers both volcanic and non-volcanic factors. First, we filtered out yield data for crops that were not healthy before the eruption due to external factors such as pests, diseases, poor fertility or seed quality, drought, frost, and hail. A Tukey HSD (honest significant difference) test with a 95% family-wise confidence level was applied to identify statistical differences in yield loss values estimated by farmers among individual crop types throughout the study area and for all three eruptions. The test showed that within the root and tuber crop group, the average yield loss values for white onion differed significantly from potato and carrot (Fig. S4). Hence, onion (white and red cultivars) was removed from the group and a new group called "onions" was created.

In the statistical analysis, we tested 23 factors ("factor") categorised into five broad categories, namely, (i) interview context (including "interviewer" and "interview number"), (ii) farmer's profile (including "farmer's gender", "farmer's age", "farmer's education level", and "total number of years in farming") and farm characteristics (including "farm area" and "household's monthly income"), (iii) tephra properties (including "tephra mass load" and "fall duration") and famer's perception of tephra hazard properties (including "tephra colour", "tephra odour", "tephra grain size", and "residence time on crop), (iv) "tephra erosion agent" and farmer's adaptation capacity (including "previous training on tephra hazard", "aid received", and "removal of tephra accumulated on the ground"), and (v) "crop phenological stage", crop management (including "crop irrigation", "fertilisation", and "use of pesticides") and "crop plot area". We included a 24th factor ("tephra mass load^2") to accommodate the quadratic impact of tephra mass load on crop yield loss in the model, given that the initial model is a linear combination of all factors. The reason for opting to incorporate farmers' perceptions of tephra grain size into our statistical analyses, as opposed to relying on the grain size analyses from Eychenne et al. (2012) and IG-EPN (Fig. S1), is that these datasets do not provide enough spatial and temporal coverage for the three eruptive periods of interest. Before the statistical analyses, we checked that factors were not correlated using the Pearson coefficient, Cramer's V coefficient, and coefficient of determination (R^2) of a one-way ANOVA to assess the correlation between continuous factors, categorical factors, and between continuous and categorical factors, respectively (Tables S4 and S5 and Fig. S5). The factor "eruptive period" was not tested as it depends on "tephra mass load" (Table 1) and its effect on crop yield loss reflects the effect tephra mass load has on crop yield loss.

To simplify the statistical treatment, we grouped similar levels (corresponding to answers provided by the interviewees) on a case-by-case basis for 13 out of the 17 categorical factors, including "farmer's age", "farmer's education level", "farm area", "household's monthly income", "tephra colour", "tephra odour", "tephra grain size", "tephra erosion agent", "aid received", "removal of tephra accumulated on the ground", "fertilisation", "use of pesticides", and "crop phenological stage" (Table S3). The levels of the five remaining categorical factors could not be simplified as they were binary or corresponded to the names of the interviewers. Statistical analyses were performed using the R 4.0.2 software (R Foundation 2022). We utilised the *stepAIC* function in the *MASS* package to determine the best-fit linear model that can explain crop yield loss in corn, potato, and legumes while using the fewest possible independent factors. The method involves a stepwise variable selection process based on the Akaike information criterion (AIC), effectively achieving a trade-off between the model's fit quality and its complexity (Bozdogan 1987; Cavanaugh and Neath 2019). We subsequently performed a type three-ANOVA analysis on the best-fit models to assess the relative importance of each factor included in the model. Based on the results of this analysis, we removed factors that did not achieve significance at the 95% confidence level (p-value > 0.05). The severity of multicollinearity among the three best-fit models was estimated based on the variance inflation factor computed with the *VIF* function in the *REGCLASS* package. The best-fit linear model was estimated for corn, potato, and legumes as they had enough individual observations (102, 68, 63), which allows for the *stepAIC* to be run (fodders, non-tree fruits, tree fruits, leafy crops, and onions have 20, 11, 32, 6, and 25 observations, respectively (Table S2)).

Results

Main crop types, crop management, and constraints to crop production

Based on the interview results, a total of 32 primary crops (including fodder) were grown in the tephra-affected region (Table S6). Corn and potato were the most frequently cultivated crops during the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods, with a 55 and 36% occurrence rate in the interviews, respectively. Additionally, growing of fodder, fava bean, pea, tree tomato, and white onion was reported in 25, 17, 12, 11, and 11% of the answers. The mean land surface area allocated to each crop type varied from 226 (for lemon tree) to 15,750 m^2 (for broccoli), and the average cultivated plot surface area was ~ 2000 m^2.

We created a crop calendar for the surveyed area, based on the data provided by the interviewees (Fig. S6). The harvest season for most fruits (such as capuli, dragon fruit, pear, blackberry, apple, peach, plum, lemon tree) typically falls between January and May, although some (like tree tomato, blackberry, apple, granadilla) are produced all year round. The annual crop sowing season (for crops such as corn, fava bean, frijole, pea, potato, melloco) is usually between August and December. Andean lupine is normally sown between February and April. A majority of farmers cultivate and harvest annual and short-cycle horticultural crops (including cabbage, carrot, squash, radish, parsley, lettuce, coriander, white and red onions, broccoli) throughout the year.

Smallholder farmers in Tungurahua utilise tractors to till the soil. Approximately half of them rely on chemical fertilisers for crop growth, whereas the majority apply organic waste (manure and/or compost) to their plots (Table S7). Around one-third of the respondents stated that they use chemical pesticides. In the absence of volcanic hazards, pest infestations (~ 30% of the interviewees), diseases (~ 20%), drought (~ 20%), and frost (~ 20%) are the primary constraints that impact crop production (Fig. S6). A large majority (~ 90%) of farmers believed that tephra emissions from Tungurahua pose the most significant threat to crop yield during an eruption (Fig. S7). However, no long-term impact of tephra on agricultural production was reported.

Farmers' observations of tephra characteristics

Figure 2 summarises the characteristics of tephra, as reported by farmers. Wide ranges of tephra fall durations were quoted for the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods, spanning from 1 to 360 days (median value of 30), 0–360 days (median value of 90), and 0–360 days (median value of 15), respectively. The corresponding deposit thicknesses ranged from 2 to 250 mm (median value of 25), 1 to 80 mm (median value of 5), and 1 to 80 mm (median value of 5). Similarly, farmers reported broad ranges of residence time of tephra on crops for the three eruptive periods: 7–420 days (median value of 90), 1–360 days (median value of 90), and 1–360 days (median

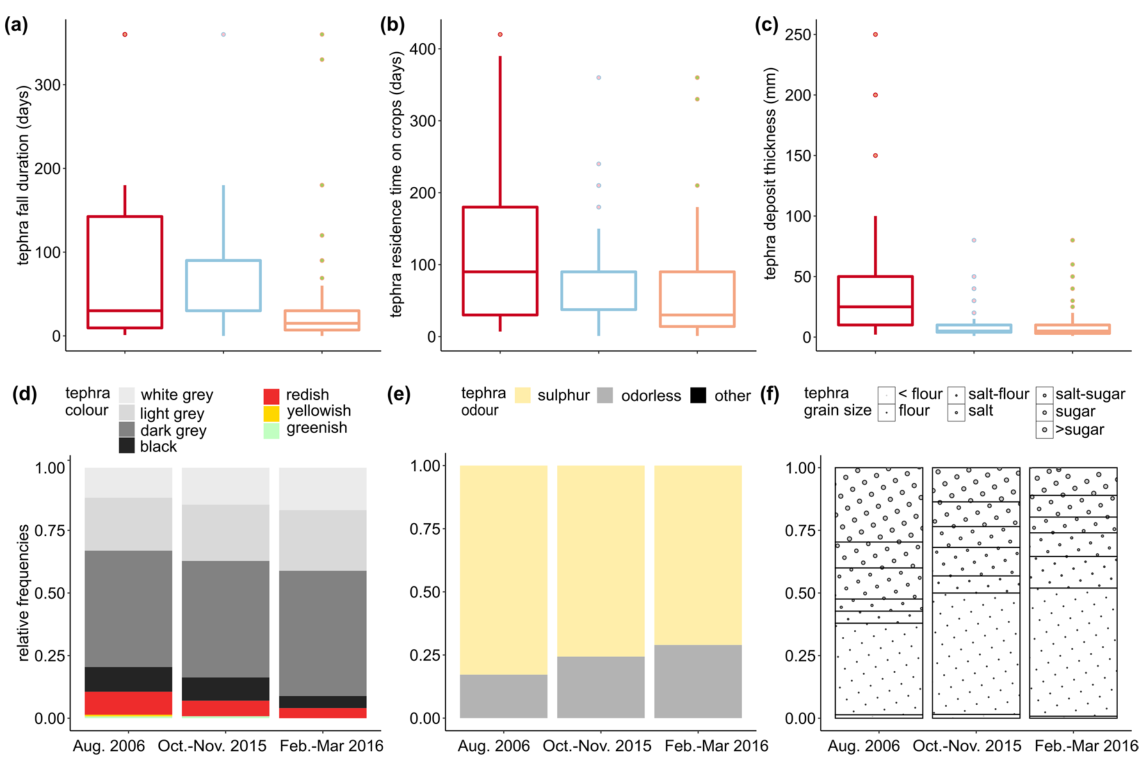

Fig. 2 Farmer's perception of the tephra hazard associated with the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods of Tungurahua volcano: tephra fall duration (**a**), tephra residence time on crops (**b**), tephra deposit thickness (**c**), tephra colour (**d**), tephra odour (**e**), and tephra grain size (**f**)

value of 30), respectively. According to farmers, tephra fallout had a colour ranging from dark to white–grey, with small proportions of black or reddish material. Additionally, many interviewees mentioned that tephra had a sulphur odour.

Approximately 50% of the respondents compared the grain size of tephra fallout from the 2015 and 2016 eruptive periods to flour, whereas the material deposited during the August 16–17, 2006, explosive activity was described as a mixture of flour and sugar (Fig. 2). This suggests the existence of two distinct tephra grain size classes, namely, fine and coarse. Some farmers (~20%) also identified larger pyroclasts, which they referred to as "cascajo", meaning gravel. The interviewees often associated tephra colour with grain size, indicating that light-coloured tephra was finer material and dark-coloured tephra was coarser.

Farmers' observations of tephra retention on crops

Around 40% of the farmers surveyed identified wind and rain as erosive agents capable of removing tephra from crop foliage, with ~20% of respondents also citing manual removal (Fig. S8a). However, wind is only effective in shedding tephra from crop foliage when the deposit is dry. Farmers pointed out that tephra particles tend to encrust leaf surfaces when the deposit becomes wet due to exposure to light rain or morning dew. This was reported as a common situation for the "flour" type (fine) tephra, which tended to cover vegetation efficiently. The interviewees also highlighted that white flour-like tephra is more harmful to crops since it adheres to foliage better than coarser tephra fallout. Unlike wind, heavy rain is capable of entirely removing tephra from crop leaves.

Farmers indicated that the duration of tephra fall has a direct correlation to how long it remains on plant foliage ($R^2 = 0.86$). Tephra on pubescent leaf crops such as corn and peach was found to have longer residence times, whereas hairless plants like fodder grass and white onion retained less tephra. Between 50 and 70% of the farmers surveyed indicated that the length of tephra residence on crop foliage is largely determined by the crop type, as the plant's characteristics, such as hairiness and organ size and shape, affect the exposure to tephra, as well as the ability of wind and rain to erode and remove the deposit from the leaf surfaces (Fig. S8c).

Farmers' observations of tephra damage to crops

Farmers reported various types of damage to their crops as a result of Tungurahua volcano's eruptions in August 16–17, 2006, October–November, 2015, and February–March, 2016 (Fig. S9). A common issue, mentioned by ~60% of the respondents, was yellowing of the leaves and stem(s), which was sometimes described as "burning" or "blackening", resembling frost burns. Tephra fallout also caused the rotting of the plant root collar, which affected all crop groups. Similarly, corn spathe, cabbage head, lettuce head, pea, and fava bean pod became black or rotted after being exposed to tephra (Fig. S10). Plant stunting was also observed. Fruit tree growers identified flower destruction caused by tephra as the most damaging effect on harvest, with 30% of fruit tree growers reporting this effect. Flowers that were hit by tephra quickly dried out and fell due to stalk abscission. Premature stalk abscission also occurred during fruit formation. Skin colour changes (due to putrefaction), skin abrasion, and tephra particles embedded in the skin were the second most important visible impacts reported for tree fruits (Fig. S10). Farmers were able to consume damaged fruits after peeling them. Tephra fallout often caused blackening and rotting of blackberry and tree tomato fruits. Potato, pea, frijole, corn, tree fruits, and non-tree fruits were identified by farmers as being the most vulnerable to tephra's detrimental effects. Tephra from the violent eruption of August 16–17, 2006, also caused direct mechanical damage to crops, such as stem and leaf breakage.

Mitigation measures for and adaptation to tephra impact on crops

Approximately 20% of farmers reported attempting to remove tephra from crops by gently shaking the plants or using a stick (Fig. S8a). However, this method was labour intensive and therefore, farmers mostly focused on cleaning fodders for their animals. When water was available, some farmers used it to wash tephra off crop leaves (Fig. S8b). Over half of the farmers modified their cropping plan or reduced the land area allocated to cultivation due to repeated tephra falls between 1999 and 2016. Certain crops, including potato, frijole, and corn, were abandoned and replaced with fodders, carrot, onion, and tree tomato. Some farmers found it impossible to grow capuli, peach, plum, apple, blackberry, and pear. The reasons for these changes varied depending on the crop. For instance, some crops (tree fruits, frijole, and corn) were susceptible to tephra damage, while others experienced an increase in plant disease (potato) or frost injuries (potato and bean). In other cases (corn and blackberry), the market price was unattractive. Farmers chose to cultivate fodders, carrot, and onion as these crops were found to be more resistant to tephra. Tree tomato production continued despite tephra fall because the production remained attractive despite lower-quality fruits.

Yield loss of crops exposed to tephra

Farmers in Tungurahua pointed out that tephra exposure led to a decrease in both the size and number of harvested products, including lettuce, carrot, bean, fava bean, white onion, potato, corn ear, and plum (Fig. S10). The quality of harvests, such as for capuli, peach, plum, and fava bean, also deteriorated as the produce acquired a bitter taste after tephra fall. Ten percent of the interviewees stated that they had to clean their production (mainly fodder) manually before selling it (Fig. S10). About 20% of the interviewees claimed that harvested plant parts could still be sold or consumed despite tephra exposure, but the market price was generally lower (Fig. S10). Tephra fall prevented 50% of surveyed farmers from generating income from crop cultivation because the product was unsaleable or nothing was produced. The major explosive period of August 16–17, 2006, destroyed most of the crop production (Fig. S10).

Farmers indicated a significant decrease in the yield of all crops that were affected by tephra. Figure S11 provides an overview of the respondents' perception of the yield loss for each crop type. A maximum yield loss of up to 100% was reported for Andean lupine, apple, blackberry, fava bean, broccoli, capuli, carrot, Chinese cabbage, coriander, fodders, frijole, granadilla, lettuce, corn, melloco, pea, pear, potato, radish, squash, tree tomato, and white onion. On average, the yield loss for fodders, root and tuber crops, onions, leafy crops, legumes, cereals, tree fruits, and non-tree fruits were 65 ± 38, 64 ± 35, 38 ± 36, 79 ± 30, 72 ± 39, 55 ± 36, 71 ± 33, and 84 ± 26%, respectively. However, in contrast to the general trend of production loss, two respondents recorded a higher yield of corn and potato for tephra mass loads ≤ 1 kg m^{-2} (or a ~ 1-mm-thick deposit) after the October–November, 2015, and February–March, 2016, eruptive periods, respectively, possibly suggesting a fertilising effect of tephra.

Factors potentially controlling yield loss of corn, potato, and legumes exposed to tephra

The models that best fit farmers' estimates of yield loss for corn, potato, and legumes have low adjusted R^2 values (0.34, 0.56, and 0.54) and include 5, 10, and 10 of the 25 factors, respectively, initially selected for the analyses (see the "Data treatment and analysis" section; Table 2). The models present reasonable multicollinearity (GVIF ≤ 11, Table S9). In total, 17 factors out of the 25 have a significant effect on crop yield loss, as evaluated from the *p*-value ranking from the type three ANOVA analysis (*p*-value < 0.05, Table 2). "Crop phenological stage" consistently appears as a factor included in the three best-fit models of crop yield loss (Table 2). Other factors variably retained in at least two of the three best-fit models for yield loss include "farmer's age", "farmer's gender", "fertilisation", "aid received", "tephra quadratic mass load", and "total number of years in farming". Finally, "previous training on tephra hazard", "fall duration", "farm area", "farmer's education level", "interview number", "interviewer", "removal of tephra accumulated on the ground", "tephra grain size", "tephra mass load", and "use of pesticides" are significant in one of the three models.

Table 2 Results of the type three ANOVA analysis, including sum of squares (sum sq), degree of freedom (*df*), *p*-value Pr (> *F*), and adjusted R^2 of the best-fit models for corn, potato, and legumes as evaluated by the Akaike information criterion

Factors	Sum sq	*df*	Pr (> *F*)	Adjusted R^2
Corn				0.34
(Intercept)	70,682.5	1	0.0000	
Interviewer	12,068.6	1	0.0002	
Tephra mass load	8534.4	1	0.0013	
Fertilisation	6905.2	1	0.0036	
Crop phenological stage	10,558.9	4	0.0119	
Tephra quadratic mass load	4160.0	1	0.0226	
Residuals	71,948.6	93		
Potato				0.56
(Intercept)	2243.1	1	0.0364	
Total number of years in farming	9963.3	1	0.0000	
Interview number	6816.5	1	0.0005	
Fertilisation	6745.3	1	0.0005	
Farmer's gender	6125.0	1	0.0008	
Farmer's age	6877.6	2	0.0019	
Tephra quadratic mass load	4347.3	1	0.0042	
Use of pesticides	3541.1	1	0.0094	
Crop phenological stage	7092.6	4	0.0108	
Help received	3015.7	1	0.0160	
Tephra grain size	2986.5	1	0.0165	
Residuals	25,801.6	53		
Legumes				0.54
(Intercept)	1737.6	1	0.0659	
Help received	11,617.7	1	0.0000	
Crop phenological stage	11,527.4	4	0.0006	
Previous training on tephra hazard	5499.9	1	0.0016	
Fall duration	5325.5	1	0.0019	
Farmer's age	6964.3	2	0.0020	
Farm area	6769.6	2	0.0023	
Total number of years in farming	4755.3	1	0.0031	
Removal of tephra accumulated on the ground	4684.9	1	0.0033	
Farmer's gender	3875.8	1	0.0071	
Farmer's education level	2245.4	1	0.0375	
Residuals	23,025.2	47		

Only the significant effects of the factor's level (*p*-value < 0.05) are detailed based on the models' summaries presented in Table S8. Regardless of the crop type, the flowering stage (level of "crop phenological stage") increases crop yield loss. Corn and potato plants suffer greater yield loss with increasing "tephra mass load"/

"quadratic tephra mass load". Interviewees using synthetic fertilisers declare higher corn and potato yield losses than those fertilising soil with manure (levels of "fertilisation"). The yield loss of potato and legumes is greater when farmers did not receive aid during the volcanic hazard (level of "aid received"), the interviewee is a man (level of "farmer's gender"), the famer is younger than 70 years old (level of "farmer's age"), or the farmer spent less years in farming ("total number of years in farming").

Discussion

Farmers' perceptions of tephra hazards

The interview results suggest that Tungurahua's farmers misperceived the duration of tephra fall for the three eruptive periods considered in the study. This is particularly obvious for the August 16–17, 2006, volcanic activity, where the average overestimation of tephra fall duration was by a factor of 60, compared to a factor of two for the October–November, 2015, and February–March, 2016, eruptive periods (Fig. 2). The misjudgement of tephra fall duration for the 2006 eruptive period may be attributed to the challenge of recalling an event that occurred over 10 years before the interviews. Furthermore, the farmers interviewed had likely been affected by the highly explosive eruption of July 2006 (VEI of 2, IG (2006b)), and frequent ash emissions were reported until the major event of August 16. The continuous activity of the volcano in July–August, 2006, could have limited the farmer's ability to specifically identify the event on August 16–17, 2006. Alternatively, it could be due to confusion between tephra fall duration and tephra residence time on crops, which was reported to be 2 to 3 months. For instance, photographs taken in Cotaló (~ 8 km west of Tungurahua volcano; (Sword-Daniels et al. 2011) show that tephra was still covering the land 2 months after the end of tephra falls, indicating a long tephra residence time, consistent with other observations of tephra particles present on crop foliage at harvest. Farmers estimated the tephra fall durations of the October–November, 2015, and February–March, 2016, eruptive periods more accurately, possibly because these were relatively recent and the last ones that occurred.

The farmers' estimates of tephra thickness appear to be exaggerated regardless the eruptive period considered. For instance, the thickness of tephra was greatly overestimated for the August 16–17, 2006, eruptive period (farmers' mean value of 41 ± 45 cm, while Eychenne et al. (2012) indicated a maximum isopach of 7 cm; Fig. 1b). Similarly, it was exaggerated for the October–November, 2015, (farmers' mean value of 11 ± 12 cm, but maximum isopach of 2 cm; Fig. 1c) and the February–March, 2016, eruptive period (farmers' mean value of 9 ± 13 cm, but maximum isopach of 0.7 cm; Fig. 1d). To improve farmers' accuracy in estimating tephra accumulation on the ground, the use of a 1:1 scale chart representing various deposit thicknesses would probably be useful.

The interview results indicate that farmers were able to distinguish between the coarseness of the tephra from the August 16–17, 2006, eruptive period and the fineness of the material erupted in October–November, 2015, and February–March, 2016. This finding aligns with the results of our GSD analyses (Fig. S2). The farmers' ability to contrast tephra fallout was probably aided by making an analogy between the grain size characteristics of the volcanic material and those of indispensable commodities such as sugar (coarse-grained) and flour (fine-grained). Moreover, by linking tephra particle size and colour (i.e., light-coloured tephra for a fine material and dark-coloured tephra for a coarser one), farmers may have better remembered the grain size characteristics of the deposit. This had already been reported around Tungurahua volcano by Ligot et al. (2022).

Types of tephra damage to crops

The results of the interviews unambiguously demonstrate that tephra fall elicits a range of negative short-term effects on crop plants, typically within one plant cycle. One of the most commonly observed effects is a change in leaf and stem colour of plants affected by tephra fallout (Fig. S9). This observation is consistent with findings from previous post-EIA studies (Miller 1967; Wilson et al. 2007, 2011, 2013; Ligot et al. 2022). Recently, Tarasenko (2018) and Ligot et al. (2022) suggested that, for tephra particles that do not carry surficial salt deposits, partial discolouration of foliage covered by tephra is likely due to lower chlorophyll contents resulting from reduced light interception by the leaves.

Approximately 10% of the farmers interviewed in Tungurahua reported growth stunting and size reduction in crops such as lettuce, carrot, frijole, broad bean, white onion, potato, corn, and plum. We believe that this effect is likely an indirect consequence of reduced light interception caused by the tephra-covered leaves, which can lead to deficient photosynthesis and altered plant growth (Figs. S9 and S10; Hirano et al. 1992; Tarasenko 2018).

The interviews revealed that irreversible damage to crops at the flowering stage was a commonly reported phenomenon, with a 30% of occurrence rate in tree fruits (Fig. S9). Farmers noted that tephra deposition, regardless of thickness, often resulted in premature flower abscission. This effect was observed not only in flowers already coated with tephra but also in pristine flowers. It is likely that flower abscission reflects the plant's physiological response to the presence of tephra on the foliage, such as the low-light conditions or stomata clogging induced by tephra cover (Li et al. 2021; Cheng et al. 2022).

Our survey also indicated that the parts of the plants that were covered by tephra often rot (Figs. S9 and S10). In fruits, this typically occurred in areas where the skin was damaged by tephra particles. Furthermore, tephra accumulation in the root collar zone (i.e., the zone between the root and the stem) can promote the growth of mould, leading to putrefaction. Previous post-EIA studies have also reported tephra-induced rotting of plant parts (Cook et al. 1981; Blong 1984; Ligot et al. 2022).

Mitigation measures for and adaptation to tephra impacts on crops

The smallholder farmers in the region affected by Tungurahua's eruptions in 2006, 2015, and 2016 had limited capacities to mitigate tephra impacts on crops due to limited water availability and, in the case of the August 16–17, 2006, activity, forced evacuation on the day of the eruption. Additionally, cleaning tephra-covered plants is a time-consuming and arduous task. Despite these challenges, farmers made huge efforts to remove tephra from fodder crops as they were concerned about potential animal illness or death, as observed in prior studies (Armijos and Few 2015; Craig et al. 2016b).

Ligot et al. (2022) have already reported on the phenomenon of farmers in Tungurahua abandoning vulnerable crops such as potato, frijole, corn, and tree fruits due to repeated tephra fall. Instead, they have opted to grow more resistant crops such as fodders, carrots, and onions. Our survey has confirmed this trend. In addition to tephra impacts, farmers cited market price, crop susceptibility to diseases, and extreme weather events as factors influencing their crop replacement decisions.

Factors controlling yield loss in corn, potato, and legumes exposed to tephra fallout

Numerous factors, including volcanic and non-volcanic, can affect crop yield loss in areas exposed to tephra fall (Jenkins et al. 2015; Wilson et al. 2015; Craig et al. 2021; Ligot et al. 2022). The stepwise model selection method we used identified the key role of the crop phenological stage in driving reduction in production of corn, potato, and legumes exposed to tephra fall (Table 2 and S8). Recent research involving post-EIA investigations (Craig et al. 2021; Ligot et al. 2022) reached a similar conclusion, but our results provide the first robust quantitative assessment to support this claim. In line with previous post-EIA and experimental investigations (Wilson and Kaye 2007; Wilson et al. 2015; Thompson et al. 2017; Craig et al. 2021; Ligot et al. 2022; Ligot et al. 2023a, b), the best-fit models we obtained for corn and potato also point to tephra mass load (or deposit thickness) as a key factor explaining yield loss. The best-fit models we obtained for the three crops also point to other volcanic and non-volcanic factors that could explain yield loss estimates, which varied depending on the crop type/group. These findings reveal the challenge of developing vulnerability functions that accurately represent crop vulnerability to tephra fall in different agricultural contexts and environmental settings.

We further explored the individual relationships between crop yield loss and tephra mass load, crop phenological stage, tephra grain size, and plant traits. These factors seem to partly explain observed crop yield loss (see the "Farmers' observations of tephra damage to crops" and "Factors potentially controlling yield loss of corn, potato and legumes exposed to tephra" sections, Table 2). We assigned yield loss estimates for various crops declared by farmers, including fodders, root and tuber crops, onions, leafy crops, legumes, cereals, tree fruits, and non-tree fruits, to each tephra mass load category based on the interview locations (Fig. 1a). To test the significance of tephra accumulation on yield, we categorised mass load values described in the isopach maps (Fig. 1b, c, and d) into three classes: < 0.5, 0.5–5, and 5–50 kg m^{-2}. These classes were defined based on a *k*-means clustering applied to the crop yield loss dataset. For fodders, root and tuber crops, leafy crops, cereals, and tree fruits, the yield loss significantly increased (Wilcoxon rank sum test, p-value < 0.05) with tephra mass load, from 39 to 87%, from 41 to 79%, from 46 to 100%, from 40 to 73%, and from 50 to 85%, respectively, when the mass load increased from < 0.5 to 5–50 kg m^{-2} (Fig. 3). The large variability ($61 \pm 37\%$) in yield loss for crops within the eight groups, as inferred for tephra mass loads < 10 kg m^{-2} (Fig. S11), could be due to mixed influences of other volcanic and non-volcanic factors (e.g., wind or rain erosion of tephra from plant foliage, use of fertilisers and pesticides, tephra grain size, plant phenological stage) and their interaction with mass load. In contrast, for tephra loads in the range 10–50 kg m^{-2}, there was less variability in the yield loss values ($89 \pm 22\%$, Figs. 3 and S11) reported by farmers. This suggests that for such tephra accumulations, other volcanic and non-volcanic factors have a lesser influence on crop vulnerability to tephra fall. Finally, our results reveal a high crop yield loss of $49 \pm 36\%$ for low tephra mass loads < 0.5 kg m^{-2} (equivalent to a deposit thickness of ~0.5 mm considering a deposit density of 1 g cm^{-3} (Eychenne et al. 2012)) (Fig. 3). This finding supports the idea that substantial production loss may occur at distal sites affected by minor tephra deposition (Ligot et al. 2022, 2023a, b).

Our statistical analysis provides compelling evidence that tephra accumulation is a critical hazard metric that significantly impacts crop yield loss. Furthermore, our findings aid to refine the relationship between tephra mass load and crop production loss. Specifically, we

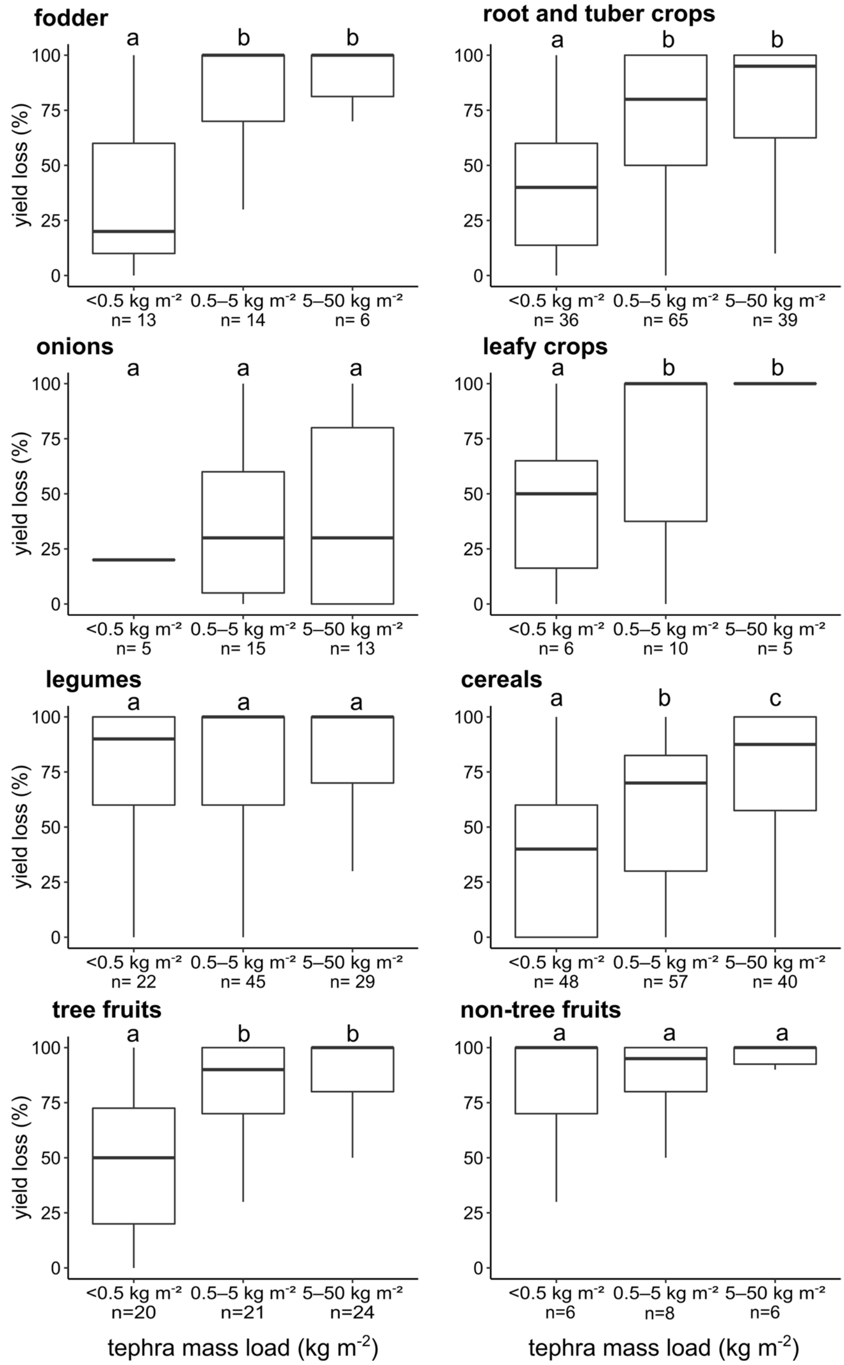

Fig. 3 Crop yield loss estimates declared by farmers for three classes of tephra mass loads for eight crop groups after the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods of Tungurahua volcano: fodders (median tephra mass loads: 0.14, 4, and 14.8 kg m^{-2}, respectively), root and tuber crops (median tephra mass loads: 0.14, 4, and 9.8 kg m^{-2}, respectively), onions (median tephra mass loads: 0.2, 1.5, and 9.8 kg m^{-2}, respectively), leafy crops (median tephra mass loads: 0.14, 4.5, and 19.6 kg m^{-2}, respectively), legumes (median tephra mass loads: 0.14, 2.5, and 19.6 kg m^{-2}, respectively), cereals (median tephra mass loads: 0.14, 2.9, and 9.8 kg m^{-2}, respectively), tree fruits (median tephra mass loads: 0.14, 4, and 14.8 kg m^{-2}, respectively), and non-tree fruits (median tephra mass loads: 0.14, 2.5, and 29.3 kg m.$^{-2}$, respectively). Results of the pairwise Wilcoxon test are indicated by letters, where groups with the same letters are not significantly different (*p*-value > 0.05)

demonstrate that exposure of root and tuber crops, legumes, cereals, tree fruits, and non-tree fruits to < 5 kg tephra m^{-2} resulted in greater yield loss values (60 ± 36, 79 ± 29, 49 ± 34, 65 ± 35, and 81 ± 27%, respectively, Fig. 3) compared to the low probabilities (0.1–0.01, 0.01–0, 0.1–0.01, 0.01–0, and 0.01–0, respectively) of reaching a 60–90% yield loss as estimated by Craig et al. (2021). Similarly, for heavier tephra accumulations in the range 5–50 kg m^{-2}, our yield loss estimates for root and tuber crops, legumes, cereals, tree fruits, and non-tree fruits (75 ± 36, 81 ± 32, 72 ± 35, 85 ± 25, and 93 ± 12%, respectively, Fig. 3) exceed those proposed by these authors (probabilities of reaching a 90% yield loss when these crop groups are exposed to 30 kg m^{-2} are low: 0.05, 0.1, 0.1, 0.05, and 0.1, respectively).

Ligot et al. (2022, 2023a, b) showed that the vulnerability of crops to tephra is strongly influenced by the plant's phenological state. In this study, we evaluated how this factor modulates yield loss in different crop groups using the information gathered from the interviews. As shown in Fig. 4, the phenological stage influences the production of root and tuber crops, legumes, cereals, and tree fruits significantly (Wilcoxon rank sum test, p-value < 0.05). For legumes, cereals, and tree fruits, vulnerability to tephra fall is highest during the flowering stage, with a median yield loss $\geq 80\%$, consistent with previous results from post-EIA investigations (Blong 1984; Neild et al. 1998; Craig et al. 2021; Ligot et al. 2022). Root and tuber crops close to final tuber mass are significantly less vulnerable to tephra compared to earlier phenological stages. In general, crop plants exposed to tephra at the seedling stage experience lower, but still high, yield loss values, averaging to ~ 50%. Non-tree fruits are vulnerable to tephra fallout at all phenological stages, enduring considerably high production loss ($85 \pm 25\%$) (Fig. 4).

The farmers in Tungurahua reported that the fine tephra, which they referred to as "flour-like", was more harmful to crops than the coarser material due to its strong ability to stick to foliage. While this observation is in agreement with recent field and experimental data (Ligot et al. 2022. 2023), the results of the statistical analyses did not confirm it as "tephra grain size" was identified as a significant factor only in the best-fit model for potato yield loss (Table 2). Similarly, the analysis of the effect of grain size on crop yield loss for three tephra mass load ranges (2–2.9, 3–4.9, and 5–7.9 kg m^{-2}) common to the 2006 (coarser tephra, Fig. 2), and the 2015 and 2016 (finer tephra, Fig. 2) eruptive periods did not show significant effect of grain size (Fig. S12).

Crop vulnerability to tephra's detrimental effects is influenced by plant traits and phenology (Magill et al. 2013; Craig et al. 2021; Ligot et al. 2022), resulting in varying susceptibilities to damage among different crop types. Our study supports this notion, as legumes, tree fruits, and non-tree fruits exhibit a greater yield loss (79 ± 30, 72 ± 33, and $85 \pm 25\%$, respectively) compared to fodders, root and tuber crops, onions, and cereals (65 ± 38, 60 ± 37, 38 ± 36, and $55 \pm 36\%$, respectively), regardless of phenological stage and tephra mass load (Fig. 4). Farmers from Tungurahua indicated that non-tree fruits, such as blackberry and strawberry, are particularly prone to tephra damage due to their prostrate habit and easily overloaded plant architecture, as well the delicate nature of their fruits. On the other hand, the high production loss of legumes and tree fruits is likely due to exposure to tephra at the flowering stage (Fig. 4).

Predicting crop yield loss in areas affected by tephra fall

The best-fit models created for corn, potato, and legumes are not satisfactory predictive models, as their coefficients of determination are consistently low, i.e. < 0.8, even when considering a high number of factors (≥ 5) (Table 2). The interview dataset primarily serves the purpose of identifying the key factors influencing crop yield loss. Among these, in agreement with previous studies, tephra mass load, crop phenological stage, and crop group emerge as the most prevalent factors (Table 2; Wilson and Kaye 2007; Wilson et al. 2015; Thompson et al. 2017; Craig et al. 2021; Ligot et al. 2022, 2023a, b). To estimate the crop yield loss based on the tephra mass load for each crop group and their phenological stage, we computed the average yield loss for three tephra mass load classes (< 0.5, 0.5–5, and 5–50 kg m^{-2}) as shown in Fig. 5. We included root and tuber crops, onions, leafy crops, legumes, cereals, tree fruits, and non-tree fruits at different phenological stages (growing, flowering, maturing, or in harvest), except for non-tree fruits where maturation and harvest stages were grouped due to data scarcity. The yield loss was assumed to be zero in the absence of tephra. For each tephra mass load class, the average yield loss is associated with the median tephra mass load of the class and a linear relationship is used to extrapolate between classes.

Knowledge of tephra mass load and crop phenological stage is important for predicting potential yield loss (YL) for crops exposed to tephra fallout. The distribution of tephra deposits in an area affected by a volcanic eruption can be estimated through surveys or using models such as Tephra2 (Bonadonna and Houghton 2005; Connor et al. 2006; Volentik 2009) . Tephra2 can also be used within the TephraProb package to create scenario-based probabilistic hazard assessments for tephra deposition (Biass et al. 2016). By utilising data from Fig. 5, we can associate a potential YL for a specific crop at a certain phenological stage with a given tephra mass load. This, in conjunction with land use maps and crop calendars for the impacted agricultural region (Fig. S6; Ligot et al. 2022), can allow for the assessment of potential economic losses due to tephra fall. However, some crops are not grown during a fixed period (as illustrated in Fig. S6), and their vulnerability cannot be easily determined a priori. This difficulty can be circumvented by using the average or median YL as a default value.

Limitations

Our comprehensive dataset highlights a significant variability in crop production loss for low tephra mass loads (Fig. S11). We attribute this variability to the interplay of several factors that affect crop vulnerability to tephra, including tephra deposit characteristics, weather conditions, pests and diseases, soil and seed quality, and plant phenotype. However, uncertainties surrounding crop YL estimates also arise from the challenges of obtaining reliable information through farmers' interviews, as previously noted ("Farmers' perceptions of tephra hazards" section). Face-to-face interviews may introduce biases due to various socio-cultural factors that can influence the respondent's answer (Rhoades 1985; Oudwater and Martin 2003). One possible approach for validating the estimates provided

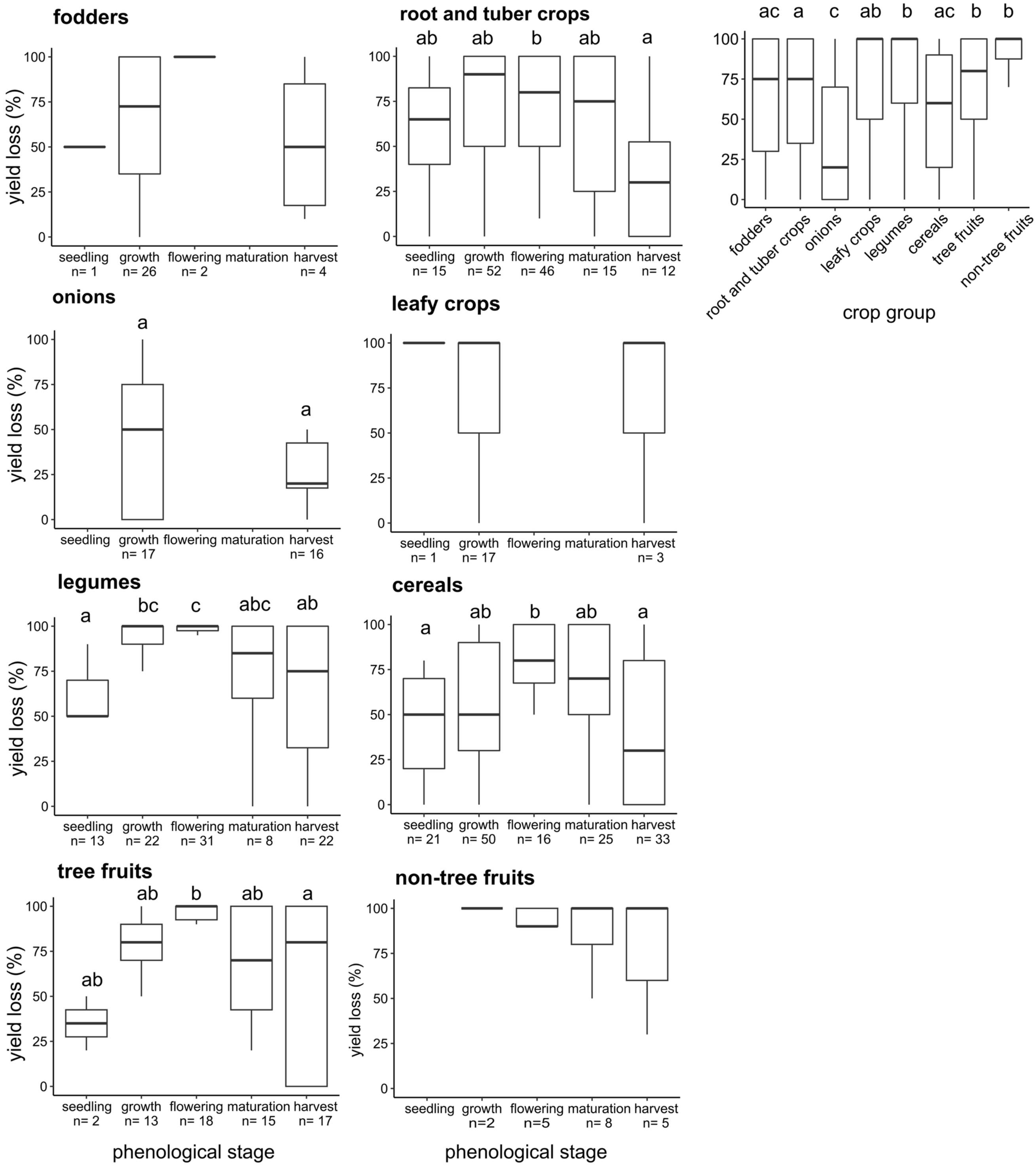

Fig. 4 Crop yield loss estimates declared by farmers for the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods of Tungurahua volcano. Yield loss estimates are presented in boxplots for the five phenological stages (seedling, growth, flowering, maturation, harvest) of the eight crop groups, as well as a boxplot for all eight crop groups regardless of phenological stage and tephra mass load (**h**). Letters denote the results of the pairwise Wilcoxon test, where groups with similar letters are not significantly different (p-value > 0.05). If there is no letter, it means there were not enough observation to perform the test

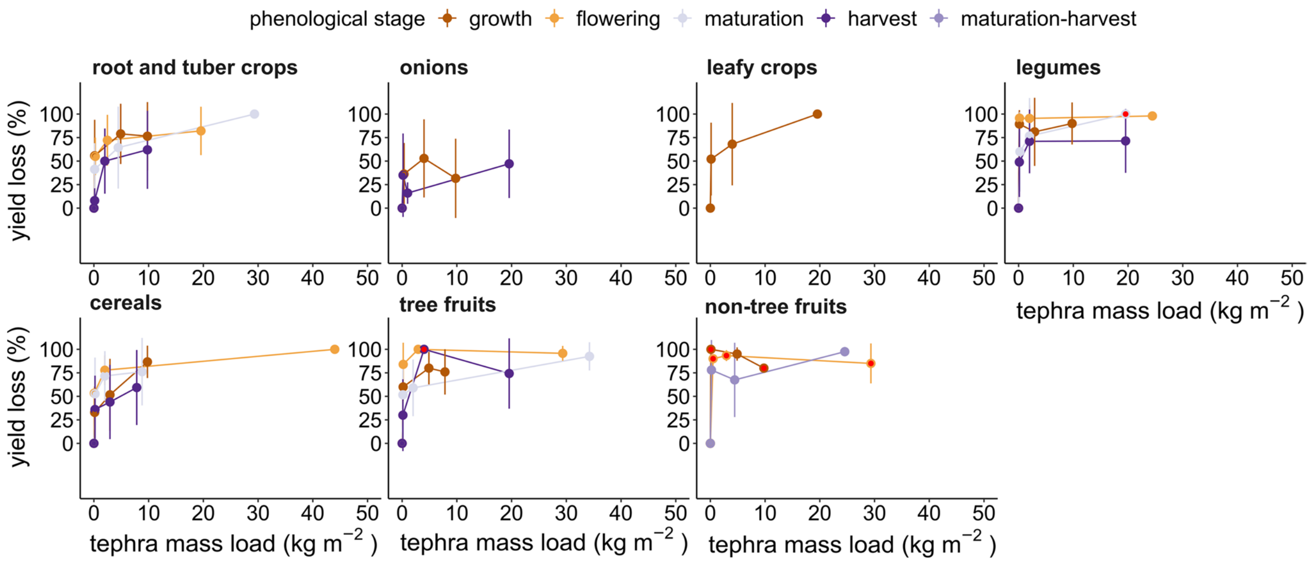

Fig. 5 Average crop yield loss with standard deviation for root and tuber crops, onions, leafy crops, legumes, cereals, tree fruits, and non-tree fruits at the growing, flowering, maturation, harvest, or maturation-harvest stage when exposed to tephra. The vulnerability function for non-tree fruits when growing is not shown due to too few observations. Red dots indicate average yield loss value computed from less than four observations

by farmers for their agricultural production is to compare them with national/regional surveys that are not subject to memory bias. Unfortunately, at Tungurahua, the annual data resolution does not allow for the capture of the eruption's effect for all crops (pers. comm.: Instituto Nacional de Estadística y Censos, July 2019). However, if farmers were to provide pre- and post-eruption agricultural production figures (as opposed to the direct yield loss reported in our survey), the annual data could be used to validate the pre-eruption crop production estimates.

While previous research suggests that tephra grain size modulates the impact on crops, our post-EIA results do not definitively confirm this factor. This may be due to a lack of contrast in tephra grain size characteristics reported by farmers in Tungurahua, which likely reflects the actual conditions of the tephra deposits emplaced in the field by the eruptions (Fig. S2). To further investigate the importance of tephra grain size in dictating crop *YL*, future post-EIA studies should target eruptions with different styles and which produce various GSD for similar tephra mass loads.

Our findings suggest that crop vulnerability to tephra varies significantly between different crops within the same crop group, as seen in the case of onion and potato and carrot, which are commonly classified as root and tuber crops, respectively (Wilson and Kaye 2007; Bignami et al. 2012; Craig et al. 2021). These variations were revealed through statistical analyses, made possible by a large dataset. To improve the accuracy of crop vulnerability assessments, we recommend that future post-EIA investigations focus on fewer crops but with a sufficient number of observations.

Although our study has some limitations, such as the reliance on farmers' reports and the potential biases of their responses, post-EIA studies that involve a large population sample provide valuable in situ data that can be tested statistically to evaluate uncertainties in crop *YL* predictions. This aspect has been missing in previous evaluations of tephra impacts on crops (e.g. Wilson and Kaye 2007; Jenkins et al. 2015; Craig et al. 2021). Additionally, our results aid to illuminate trends and processes of tephra damage to crops, which can inform the design of controlled experiments to elucidate specific impact mechanisms. Following Craig (2015), standardised guidelines for conducting post-EIA studies would allow for data collection that can be compared across case studies. This effort would also facilitate the creation of agricultural impact database for volcanic hazards, which would gather information from both previous qualitative and semi-quantitative studies (e.g. Wilson et al. 2007, 2011, 2013; Magill et al. 2013; Blake et al. 2015; Craig et al. 2016a; Craig et al. 2016b; Ligot et al. 2022) and quantitative results such as those presented here.

Conclusions

Through farmer interviews, we found that the quality and yield of crops cultivated in a ~ 800 km^2 area were impacted by tephra deposits from the August 16–17, 2006, October–November, 2015, and February–March, 2016, eruptive periods of Tungurahua volcano. Farmers tended to confuse tephra fall duration and tephra residence time on vegetation and exaggerated the thickness of the deposits that impacted their crops. Presenting a graphical chart during face-to-face interviews could improve the accuracy of tephra thickness estimates in post-EIA studies. In contrast, farmers were able to describe tephra grain size relatively accurately when an analogy with the grain size of essential food commodities (sugar and flour) was suggested. The farmers identified a range of tephra damage to crops, including leaf and stem colour changes, plant growth stunting, flower abscission, and rotting of plant part, with the type and severity of damage varying with crop type and phenological stage. Although farmers implemented some mitigation strategies, these did not alleviate impacts significantly.

Our study confirmed tephra accumulation on the ground as a key hazard metric for predicting production loss of crops exposed to tephra. However, for tephra mass loads < 10 kg m^{-2}, other volcanic and non-volcanic factors increasingly control impact, which explains the large variability in the *YL* values reported by farmers for crops located in areas of low tephra deposition. We identified plant phenological stage, particularly the flowering stage, and specific traits (plant habit/architecture and organ delicacy) as key controls of crop vulnerability to tephra.

We demonstrated that a post-EIA study involving a large population sample can provide insights into the volcanic and non-volcanic factors that control crop *YL* after a tephra fall event. It also allows for better quantification of uncertainties in production loss predictions. We suggest that efforts should be made to couple field observations with experimental approaches to better understand the mechanisms of tephra impact on crops. This will aid in the development of reliable risk models for tephra-induced crop damage to crops. Finally, we advocate the use of standardised guidelines for post-EIA studies to collect data that can be compared across case studies.

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Declarations

Competing interests The authors declare no competing interests.

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