EGUsphere, author comment AC1
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Reply on RC1

Noa Ligot et al.

Author comment on "Grain size modulates volcanic ash retention on crop foliage and potential yield loss" by Noa Ligot et al., EGUsphere, https://doi.org/10.5194/egusphere-2022-687-AC1, 2023

Reviewer 1's comments

LITERATURE

R1.1

In the introduction, information from post-eruption field assessment are shortly reviewed, as well as some papers focusing on the effect of dust/ash on plant more specifically (line 74-90). However, in the discussion, the authors point out to the existence of previous field and experimental work more specifically related to their research (by Miller et al., Johnson et Lovaas, Hirano et al.). It is needed to shortly mention these previous research in the introduction to justify that 'ash grain size, leaf pubescence and ambient humidity have been suspected to affect ash retention on foliage' (lines 91- 92)

The following references have been inserted:

Line 97: Thompson, J. R., Mueller, P. W., Flückiger, W., and Rutter, A. J.: The effect of dust on photosynthesis and its significance for roadside plants, Environ. Pollut. Control, 34, 171-190, doi: 10.1016/0143-1471(84)90056-4, 1984.

Line 97: Hirano, T., Kiyota, M., and Aiga, I.: Physical effects of dust on leaf physiology of cucumber and kidney bean plants, Environ. Pollut., 89, 255-261, doi: 10.1016/0269-7491(94)00075-O, 1995.

EXPERIMENTAL PROCEDURE

R1.2

The methodology section describes in quite some details the novel experimental protocol implemented in this research. However, some elements could be further clarified. Additionally, a figure (or photo) representing the entire setup, including the device to spread the ash and the imaging system, would help the reader to understand the protocol.

We thank the reviewer for his/her suggestion. A new figure (Fig. S4) showing the experimental setup is provided as Supplementary materials.

R1.3

- Line 111: specify the typical height of plants and typical surface areas of leaves at the time of experiments;

Information on the height of tomato and chilli pepper plants before ash application is now provided.

Estimating the surface area of individual leaves is not straightforward as it varies with the leaf position on the stem. Instead, we provide the surface area of tomato's and chilli pepper's foliage as estimated by performing image analysis (using ImageJ) of the plant photos.

Line 121: They were exposed to ash six weeks after sowing, when tomato and chilli pepper plants were at the seven- and eight-leaf stage, respectively. The corresponding plant heights were ~40 and ~30 cm. The foliage surface area was ~400 and ~100 cm² for tomato and chilli pepper, respectively;

R1.4

- Line 119: crushing phonolite rocks: did you check the morphology of the produced particles using SEM after crushing and compared to actual ash? Although I understand that crushing might be the best way to generate large ash fraction, the morphology of particles might influence their interaction with leaves.

The reviewer makes a good point. Using crushed rock as a surrogate for ash from explosive eruptions allowed us to carry out multiple tests while reducing the number of uncontrolled variables. We have examined the phonolite powder obtained after crushing (i.e. the ash surrogate) by scanning electron microscopy (SEM). We now provide SEM images of this material and for each size fraction (≤90, 90-125, 125-250, 250-500, 500-1000, 1000-2000 µm) (Fig. S1 in the Supplementary materials). Regardless of the ash grain size, most particles are blocky, but rounded or platy shapes also occur. Similar shape characteristics are commonly reported for ash particles from explosive eruptions (Wohletz, 1983; Wohletz and Heiken, 1992; Coltelli et al., 2008; Nurfiani and Bouvet de Maisonneuve, 2017). Blocky particles usually result from fragmentation and quenching of magma, whereas elongated and rounded shapes are related to ductile deformation. Vesicular particles (concave and with an irregular shape) are also a typical product of explosive eruptions; they are formed by the rupturing of vesiculated magma in the volcanic conduit. However, such particles cannot be generated by crushing a solid rock and therefore, they were absent in our ash material. While we acknowledge that this is a limitation of our experimental approach, we argue that it does not jeopardise the validity of our observations as ash deposits from explosive eruptions always contain a mixture of particle shapes. It may be speculated that the irregular shape of vesicular ash could favour its retention on leaf surfaces, in particular when these are pubescent (hairy) or wet. Thus, for a given ash mass load, the presence of vesicular particles could lead to higher retention compared to what we measured experimentally. Our results may then be regarded as conservative estimates.

We have added new text to the Materials and methods (Lines 134-141) and Discussion (Lines *307-312*) sections, where we present briefly the shape characteristics of the ash material used in our study and discuss the potential limitations, respectively.

Lines 134-141: The shape characteristics of the six ash size fractions obtained by grinding the Laacher See phonolite were examined by scanning electron microscopy (SEM). The SEM images (Fig. S2) reveal that, regardless of their size, most particles are blocky, but rounded and platy shapes also occur. Similar shapes are commonly reported for ash *particles from explosive eruptions (e.g., Wohletz (1983); Coltelli et al. (2008); Nurfiani and Bouvet de Maisonneuve (2017)). However, the vesicular ash type that is also often associated with the fragmentation of gas-rich magmas cannot be generated by rock grinding and was absent in our experimental ash material.*

Lines 307-312: As mentioned above (section Material and methods), an inherent limitation of our experimental study is that the ash material did not contain the vesicular particles that are usually found in various proportions in ash fallout from explosive eruptions. We speculate that the irregular shape of vesicular ash could enhance retention on foliage, perhaps even more so if the leaf surfaces are pubescent or wet. Thus, our measurements may be regarded as conservative estimates.

R1.5

- Ash loading of 570 g m-2 (line 129): why did you select such loading that could be considered very low.

Our research objective was twofold: (i) to assess how ash grain size, leaf pubescence and humidity conditions at leaf surfaces influence the retention of ash in tomato and chilli pepper plants, and (ii) to use this information to propose a conceptual model for predicting crop yield loss when ash does not threaten plant integrity. We conducted trials and noticed that for ash loads ≥ 1000 g m^{-2} (equivalent to a deposit thickness of ~1 mm, assuming a deposit bulk density of 1 g cm^{-3}) tomato and chilli pepper plants were affected by lodging. Obviously, this phenomenon had to be avoided as much as possible. Therefore, we tested lower ash mass loads and found that with ~570 g m^{-2} (~0.6 mm), we could replicate the experiments satisfactorily. If this ash load seems low, it represents well a situation commonly encountered at distal sites (and therefore, across a wider area) affected by ash fallout. Until our study, there were no data on the potential impact on crops of such low ash mass loads/thin deposits. Thus, our measurements contribute to fill this gap in knowledge.

We have added the following sentence to the *Material and methods* section:

Lines *148-159: An ash load of ~570 g m^{-2} was selected for the experiments. Assuming a bulk density of 1 g cm^{-3} for the ash deposit (Eychenne et al., 2012), this corresponds to a relatively thin deposit of ~0.6 mm (i.e. considering a bulk deposit density of 1 g cm^{-3}, Eychenne et al. (2012)), best representing accumulations encountered at distal sites (and over wide areas) affected by ash fallout from explosive eruptions (Fierstein and Nathenson, 1992; Jenkins et al., 2022). Pre-tests carried out with higher ash loads (≥ 1000 g m^{-2}) already led to lodging of some tomato and chilli pepper plant specimens, a phenomenon that needed to be avoided in order to maximise the experiment's reproducibility. Neild et al. (1998) and Craig (2015) consider that an ash mass load of 6-30 kg m^{-2} on plants leads to mechanical damage. Our observations indicate that lower loads can affect crop plants. In other words, the threshold value above which mechanical injury occurs varies with plant phenology (i.e. the combination of genotype and environment).*

R1.6

- Could it be expected that at larger loading, larger surface of leaves be covered until the grainsize does not matter anymore (see main comment below). Further discussion on the potential impact of ash loading on the observed relationship would be useful.

The reviewer makes an interesting comment. We contend that for intermediate ash grain sizes (90-500 µm), greater ash mass loads may lead to higher ash retention on plant foliage. More particles may accumulate along the leaf primary and secondary veins as these less elastic tissues are able to absorb the kinetic energy of impinging ash particles with an intermediate grain size. However, we believe that a higher loading of ash ≤90 µm will not lead to higher retention because a portion of the leaf surface area (~10% for tomato and chilli pepper in our experimental conditions as estimated from the data shown in Fig. 1) is too vertical to retain the ash particles. Due to their high kinetic energy, coarse particles (≥500 µm) tend to lodge on less elastic structures such as leaf folds. We predict that the retention of coarse ash on foliage will be limited by the number of leaf folds and thus, will probably not increase significantly for higher ash load values. Based on these arguments, we anticipate that, for ash loadings >570 g m^{-2}, the exponential relationship between ash grain size and ash retention will no longer hold and instead, a linear function would provide a better model. The fine and coarse fractions would then correspond to the maximum and minimum retention values, respectively.

We have added new text in the *Discussion* section:

Lines 269-280: This relationship was established for a single ash mass load (~570 g m^{-2}). For ash in the intermediate size range, a higher load could result in enhanced retention of the particles, particularly along the primary and secondary leaf veins as these consist of less elastic tissues that can better absorb the kinetic energy of impinging ash particles of intermediate grain size. However, for fine ash, we do not expect more retention to occur if tomato and chilli pepper leaves were exposed to higher loads because a large proportion of the foliage is comprised of leaves that, due to their steep angle, cannot retain ash particles efficiently. As mentioned earlier, coarse ash particles tend to lodge primarily on leaf folds. Thus, their retention on foliage will likely be limited by the number of leaf folds. Overall, we anticipate that for ash load values >570 g m^{-2}, the exponential dependence of ash retention on ash grain size will start to degrade and instead, a linear relationship would be a better model.

R1.7

- Line 133: "through a 2 cm-mesh sieve" – is this correct? 2 cm seems extremely coarse relative to the ash used and would not help to distribute the ash evenly across the device.

Yes, it is correct. The mesh sizes of the sieve sitting on top of the PVC tube and of the three sieves installed inside it are 2 and 1 cm, respectively. This set up allowed the formation of a uniform ash deposit on the ground.

The text was slightly modified as follows:

Line 162-166: The ash fractions <1000 µm were poured carefully through a 2 cm-mesh sieve installed on the top of the PVC tube. Bouncing of the ash particles passing through the three inner 1-cm sieves allowed formation of a uniform deposit. Application of the coarsest ash (1000-2000 µm) was carried out with the same device, but the inner meshes were removed.

R1.8

- Lines 135 and following: the protocols should be more specific for what concern the timing and location of different actions. What was the duration between the spraying of water on the leaves (for wet condition), the spreading of the ash and the acquisition of the pictures? Did these action follow each other within minutes or were there hours/days in between? Was spreading of ash conducted at the same location of the acquisition of the picture or was the plant displaced?

We thank the reviewer for his/her suggestion. We created a new figure (Fig. S4) in the Supplementary materials which indicates the timing and location of each step performed in order to collect the experimental data.

The main text was modified as follows:

Lines 170-172: Water spraying of the plant foliage, ash application and photo acquisition all took place within the black chamber. Less than five minutes elapsed between the spraying operation and photo acquisition of the ash-treated plant (Fig. S4).

R1.9

- Line 145: precise here that image is acquire before and after ash fallout (mentioned later on, but needed here for better understanding).

We have revised the text as follows:

Lines 183-185: We analysed the digital photos taken just before and after ash application with ImageJ 1.52 (Schindelin et al., 2015). The foliar cover, a measure of the vertical projection of exposed leaf area, was estimated using a dedicated macro (https://github.com/NoaLigot/ImageJ-macro.git).

R1.10

- Ash retention: was there any way to quantify the proportion of ash that was retained on the leave versus the ash that reached the ground? Were the plant weighted before and after the ash fallout?

In our experiment, the mass of ash loaded into the PVC tube is higher than that collected by tomato and chilli pepper's foliage. This simply reflects the fact that an unknown amount of the ash applied is not retained by leaves. However, using the proportion of ash found on leaves when referring to ash load would not be useful for developing models of impacts. The reason is that the metric used for describing the ash hazard intensity in risk analysis is ash accumulation (i.e. mass load or thickness, Wilson and Kaye, 2005; Jenkins et al., 2015) on the ground (and not on plant foliage), as measured directly in the field or estimated from ash dispersion/fall models. In our study, the ash hazard intensity would correspond to an ash mass load of ~570 g m^{-2}. Knowledge of the precise amount of ash retained on crop leaves would be needed for developing a detailed process-based understanding of impacts, but this falls out of the scope of our research. Here, we dismiss the reviewer's comment.

R1.11

- Lines 160-165: issue of leave bending. Authors report that some of their measurement returned higher 'green leaf surface' after ash exposure than before, claiming that this is due to movement of leaves and camera during image acquisition. As these issues probably affected all their measurement, the accuracy of the documented covered leave surface could be derived by considering the noise observed for experiments were the retention is close to zero. Additionally the issue of leave bending should receive further attention in the description of results: did significant bending or change in orientation of leaves were observed? For which grain size? Beyond the impact on the imaging procedure, the bending would also directly influence the potential of retention of ash? This is mentioned on line 266 ('which pulls a leaf downward') but no comment is made on whether this process was observed during experiments;

We appreciate the reviewer's comment. The errors linked to camera positioning and image analysis were systematic. In order to minimise these, constant light conditions were used and the results of the image analysis were validated based on a comparison to the RGB photos. Leaf bending occurred only when fine ash (<90 µm) was applied to tomato and chilli pepper; it did not affect the plants in any of the other ash treatments. Plants were tutored in order to limit stem and leaves movements. The variability in the measurements was similar across the ≤90 and ≥500 µm ash size fractions tested (Fig. 1). Therefore, we argue that leaf bending had a negligible impact on the results. In the original submission, we probably drew too much attention on the potential influence of leaf bending on ash retention. We have rectified this by removing Lines 160-165 from the original manuscript. Moreover, since we cannot disentangle errors related to camera positioning and image treatment from the "natural" data dispersion, we have modified Figs. 1, 2 and 6, Tables S1 and S2 and Fig S5 in order to display the actual data variability rather than omitting the negative values (as it was done in the original submission).

OTHER FACTORS

R1.12

- Ash loading: authors decide to work with a single ash loading for all experiments. They properly argue that they select an ash loading that is below the threshold for physical damage for the plant (is such threshold well defined? Is it plant specific?).

Here, the reviewer points to a deficiency in knowledge. The ash mass load threshold above which crop plants undergo mechanical damage is poorly constrained. It is plant-specific since it depends on plant's phenotype (i.e. the combination of genotype and environment). Previous field-based studies, i.e. Neild et al. (1998); Craig et al. (2021), suggest ash deposit values on the order of ten kilograms per square meter, e.g., ~30 kg m^{-2} (assuming a deposit bulk density of 1 g cm^{-3}) for fruiting crops such as tomato and chilli pepper and 6-25 kg m^{-2} for horticultural plants. However, in our experiment, tomato and chilli pepper at the seven- and eight-leaf stage, respectively, were already affected by lodging when exposed to much less ash, i.e. ~0.6 kg m^{-2}. New studies are needed to better characterise the exposure conditions under which a crop plant may suffer from mechanical damage.

We have clarified this in the Material and methods sections as follows:

Lines *148-159: An ash load of ~570 g m^{-2} was selected for the experiments. Assuming a bulk density of 1 g cm^{-3} for the ash deposit (Eychenne et al., 2012), this corresponds to a relatively thin deposit of ~0.6 mm (i.e. considering a bulk deposit density of 1 g cm^{-3}, Eychenne et al. (2012)), best representing accumulations encountered at distal sites (and over wide areas) affected by ash fallout from explosive eruptions (Fierstein and Nathenson, 1992; Jenkins et al., 2022). Pre-tests carried out with higher ash loads (≥ 1000 g m^{-2}) already led to lodging of some tomato and chilli pepper plant specimens, a phenomenon that needed to be avoided in order to maximise the experiment's reproducibility. Neild et al. (1998) and Craig (2015) consider that an ash mass load of 6-30 kg m^{-2} on plants leads to mechanical damage. Our observations indicate that lower loads can affect crop plants. In other words, the threshold value above which mechanical injury occurs varies with plant phenology (i.e. the combination of genotype and environment).*

R1.13

Assumption is made that the relationship between grainsize and foliage cover found for this ash loading would be valid also for other loading (or at least the type of relationship – lines 231-32). Would the retention of ash not relatively increase with increasing ash loading? Until a point were all the leave surface are covered irrespective of grainsize?

This comment duplicates a remark made earlier by the reviewer (R1.6). We kindly refer the Editor to our reply above.

Could it be assumed that once a first layer of ash is retained on the vegetation, the effect of grainsize on accumulation would not be valid, the ash particles creating their own roughness at the surface? Further discussion on the ash loading for which the observed role of grainsize might be valid should be further discussed.

For a natural ash deposit, with particles varying widely in size, the formation of a fine ash deposit at the leaf surfaces could facilitate subsequent accumulation of coarser ash if the deposit is able to absorb the kinetic energy of the impinging particles. For smooth leaf plants such as chilli pepper, a such process would increase leaf surface roughness. In order to test this, new experiments in which ash retention is quantified for a material with a broad grain size distribution would be needed.

Similarly the reader should be reminded that the yield loss mentioned are only valid for the ash loading used in the experiment and that ash loading will most probably be a significant parameter in controlling foliage cover.

We agree with the reviewer's suggestion. We have revised the text accordingly:

Line 345: *Our experimental results indicate that ~570 g m^{-2} of fine ash can readily cover the upper side of leaves (Fig. 2).*

Line 396: *To illustrate our approach, we estimated CYL_% for tomato and chilli pepper plants exposed to ~0.6 mm (~570 g m^{-2}) of ash.*

Line 542: *We also showed that, for a given ash mass load (~570 g m^{-2}), the leaf surface percentage covered by ash is an exponential decay function of grain size of which the parameters are influenced by leaf pubescence and humidity conditions at leaf surfaces.*

R1.14

- Residence time of ash: very limited attention is giving to the time component; Authors consider the timing of the ash fallout relative to the growth of the plant, but not the duration of the ash retention on the leave (assuming early senescence of ash covered leaves). As the duration of residence not been considered in previous study? For how long does the ash need to cover the leave to cause decay? In intro (line 87-88) and discussion (line 449-450) this issue of duration should be shortly mentioned (in relation to wind/rain 'erosion')

While the reviewer's comment is valid, it does not apply directly to our study. In natural conditions, an ash deposit on leaves can be remobilised by the action of the wind and/or rain. The time necessary for eliciting leaf damage has never been studied, but undoubtedly varies depending on the phenotype of the plant. More information (which could be acquired in controlled experiments) on the timing of ash fallout and subsequent impact on crop foliage would be needed in order to factor residence time in our model of potential yield loss. The importance of ash residence time on crop foliage in dictating impacts was already mentioned in the original submission:

Lines 521-527 (Discussion): *In addition, in the natural environment, wind- and rain-driven erosion processes can remove ash deposited on foliage. Conversely, light rain may induce crusting of ash, prolonging its residence time on leaves (Miller, 1966; Ayris and Delmelle, 2012; Le Pennec et al., 2012; Ligot et al., 2022). The significance of these environmental variables in controlling ash retention time by leaves has never been assessed quantitatively, calling for further field and experimental investigations linking ash residence time on plants and impact.*

R1.15

- Physical integrity: authors systematically mention that they consider impact of ash on foliage for loading below the loading required to affect 'plant integrity' (line 99). However, this threshold is not clearly defined (line 304: 'cm-thick'). I guess this threshold will be specific for each plant and development stage of a plant. This could be further clarified in discussion.

This comment is similar to R1.12. We kindly refer the editor to our reply above.

IMPLICATIONS

R1.16

In both the introduction (lines74-75) and conclusion (line 491), authors claim that understanding and quantifying the retention of ash on crop foliage represent an essential step in mitigating the impact of eruption on agriculture. I agree that the presented results will contribute to better assess quantitatively the potential impact of ash fallout on crops (reduced yield), however it is unclear to me what the author consider as potential mitigation measures that could be derived from these results. The mitigation actions should be specified or the focus should be on the impact assessment.

The reviewer makes a good point. The wording "mitigation measures" is not appropriate. Our experimental data allowed us to propose a model to predict potential crop yield loss based on two ash fall intensity metrics (i.e. mass load and grain size). As such, our study does not provide direct insights into the mitigation measures to be implemented by farmers after ash fallout. Nevertheless, we argue that controlled experiments allow for the production of unique datasets that can inform decision making, for instance, in relation to aid allocation, land-use planning, or parametric insuring.

The text was adjusted accordingly (Lines 75-78 and 562-565):

Lines 75-78: *These limitations are hindering the development of accurate process-based risk assessment models that can inform targeted strategies to build resilience of agriculture-based community in the case of an explosive eruption; for example, in relation to aid allocation, land-use planning and insuring.*

Lines 562-565: *Acquiring this knowledge will significantly enhance our capacity to estimate ash-related risks to crops accurately. Governments and payout agencies need such assessments in order to develop and implement effective risk reduction strategies for ashfall damage to crops in volcanically active agricultural regions.*

SMALL EDITS

- Abstract is well written but could be shortened both in the problem statement and the results implication

We agree with the reviewer. We have removed three sentences from the abstract to make it shorter.

- Line 41: 'farming activities ARE exposed'

Corrected

- Line 48: 'economic loss' – in country with subsistence farming the issue of food shortage would also have to be considered.

The text has been revised as follows:

Lines 46-49: As a result, crop fields impacted by ash fall produce lower or poor-quality harvests that can translate into significant economic losses to farmers and food shortages at the local or even regional scale, and even more so when subsistence agriculture dominates (Neild et al., 1998; Wilson et al., 2007; Ligot et al., 2022).

- Line 76-79: which ash thickness/loading is considered to calculate these areas of crop affected?

The text has been revised as follows:

Lines 79-81: *Jenkins et al. (2022) estimated that an explosive eruption of VEI 4 (Volcanic Explosivity Index (Newhall and Self, 1982)) on the island of Java, Indonesia, has on average a 50% probability of affecting ~700 km^2 of crops with 5 kg m^{-2} of ash.*

- Figure 1: specify the number of experiments represented by each boxplot (is it 15?). Explanation of how to read the chamber plot (median, 25-75th quantile) should be added to caption.

The caption of Fig. 1 has been modified to include the required information:

Lines 220-222 *Each boxplot represents 15 repetitions. The median value sits within the box and represents the centre of the data. Fifty % of the data values lie above the median and 50% lie below the median.*

- Figure 3: add scale bar or specify the area imaged in the caption.

The surface area of the image (~800 cm^2) is mentioned in the caption of Fig.3.

- Line 285: figure 1 highlight that surface wetness has more influence on retention for chilli pepper than tomato plan. This observation should be discussed here: I guess that leave pubescence and wetness act in a similarly way, so that wetness induces lower additional retention with tomato plants.

Here, the reviewer evokes a complex topic. A detailed discussion on the relative importance of leaf hairiness and wetness in favouring ash retention would first require a precise description of leaf surface characteristics (e.g., hydrophobicity, leaf hair density, and 3D characterisation). Such data are plant/plant variety-specific, and are not available for the tomato and chilli pepper species used in our experiment. More experiments (at various humidity conditions at leaf surfaces) would also be needed to identify the main controlling factors. The reviewer's request falls out of the scope of our study, and at this stage cannot be addressed.

- Line 320: explain what is the 'harvest index'.

A definition of the harvest index is included in the revised manuscript:

Lines 379-380: *[…] harvest index, i.e. the fraction of the total aboveground biomass allocated to the harvested parts of the plant*

- Line 335-340: explain here how the impact of ash on the plant growth is simulated through leave senescence followed by new leave growth.

We have clarified this point in the revised manuscript:

Lines 383-386: *We consider two effects of ash on plant yield: reduction in LAI and premature biomass senescence. The former leads to lower accumulated biomass after formation of the ash deposit, whereas the latter is responsible for a loss of biomass that accumulated prior to ash fall.*

We also describe in more details the temporal dynamics of *LAI*:

Lines 407-411: *On the day of the eruption, the LAI is reduced by an amount corresponding to the percentage of foliar cover coated with ash. On the following days, it re-increases as new leaves formation resumes at a rate similar to that before exposure to ash. If time permits, the LAI may reach a value identical to that of a plant that would not have received ash.*

- Figure 6: provide also the results for chilli pepper in the main text, these are important results.

The experimental results obtained for chilli pepper have been added to Fig. 6.

References

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