



## Report on geochemical characterisation of volcanic ash from Cumbre Vieja, La Palma, for the assessment of respiratory health hazard

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Volcanic ash has several hazardous characteristics that may impact human and animal health. We report the results of a geochemical assessment of key hazardous characteristics of 16 volcanic ash samples erupted from Cumbre Vieja, La Palma, between 19 September – 16 October 2021. The analyses are an essential first step in assessing health risk from volcanic eruptions because they allow a rapid screening of the physicochemical characteristics that have the potential to cause harm. The report is in two sections: Part 1 presents analyses related to respiratory hazard, while Part 2 presents analyses relevant for contamination of drinking water and ingestion hazards for livestock. The main authors (Horwell, Damby & Stewart) are directors of the International Volcanic Health Hazard Network ([www.ivhhn.org](http://www.ivhhn.org)) and have conducted and published extensive research to develop and test techniques for rapid analysis of volcanic ash for health hazard assessment.

### Part 1 Summary - Respiratory health hazard assessment of volcanic ash

- **The ash contained little inhalable-sized material.** Morphological examination identified fibre-like particles in some samples, however these comprise calcium sulfate, volcanic glass and other silicates that are not related to asbestos. Leachate assessment for respiratory hazard found low concentrations of potentially toxic elements (PTEs) compared to analyses from other eruptions.
- Collectively, these data indicate that the ash has low potential to cause respiratory harm directly, although people may experience discomfort from inhaling the particles. Note that these conclusions only apply to unmodified ash. Wind remobilisation and human activities (e.g., driving on ash) over the coming months to years may produce finer-grained, inhalable particles. This study did not analyse the possible hazards of volcanic gas and aerosols (either direct from the volcano, or from lava ocean-entry). A change in the eruptive style and fragmentation mechanism (e.g., with changing magma composition or magma-water interaction) could change this hazard assessment.
- **A precautionary approach should be taken with efforts to reduce exposures to the airborne volcanic emissions, particularly for those in vulnerable<sup>1</sup> groups or who work in outdoor occupations or who are involved in ongoing ash clean-up activities. Personal exposure and airborne concentrations should be monitored to assess the evolving and chronic health risks. Further evaluation of ash particle properties should be conducted if the eruption generates finer-grained ash.**

### Part 2 Summary - Potential for contamination of water sources and ingestion hazards for livestock

- To assess the potential of the ash to contaminate water sources, a deionised water leach was conducted to determine the concentrations of rapidly released elements. To assess the bioaccessible fraction (the

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<sup>1</sup> Vulnerable groups include children, elderly people, those with pre-existing respiratory/cardiovascular disease and pregnant women.

fraction that is soluble in biological conditions) of PTEs to grazing livestock, a simple gastric leach was conducted on a subset of three samples.

- **Concentrations of water-extractable fluoride (F) were high** in comparison to global median values, **implying a potential to contaminate water sources**. This is most notable for samples from early in the eruption but concentrations of leachable F from all samples are higher than median values. Concentrations of other measured PTEs were generally low in comparison to global values, except for barium, bromide and zinc in some samples. For almost all elements, HCl-extractable concentrations were greater than water-extractable concentrations, in some cases (Al, Cr, Fe, Ni) by more than tenfold.
- It is possible that **livestock health could be affected by the high levels of adsorbed fluoride and zinc** if ash is ingested along with feed. If livestock health is of concern, further assessment of exposure may be warranted to determine the potential for toxicological impacts.

## Part 1

### Respiratory health hazard assessment of volcanic ash

#### Background

Cumbre Vieja (La Palma, Canary Islands) began erupting on 19 September 2021 when a fissure system opened. The activity since then has been both effusive (passive eruption of lava and gases via fountaining and direct flows from active vents) and explosive (fragmentation of magma to produce volcanic ash and gases, mainly from the highest vent/s). The explosions have varied in their intensity (from low-intensity Strombolian bursts to high-intensity paroxysms) and, hence, in the amount of ash that has been generated. Dependent on wind direction, the ash has been deposited primarily to the west of the vent but, on occasion, more widely across the island. Reports have been received of ash deposition as far as Gran Canaria (>200 km from the vent).

Acute (short-term exposures) to volcanic ash may cause throat/lung irritation, cough and bronchitic symptoms in healthy people, and those with respiratory diseases (e.g., bronchitis and asthma) may experience exacerbation of pre-existing symptoms (Horwell and Baxter, 2006). Ash can also have several possibly harmful physicochemical characteristics, if inhaled. Here, we report on particle size (to assess the abundance of respirable particles), ash morphology (to identify any fibre-like particles associated with asbestos minerals), and readily soluble potentially toxic elements (PTEs) on particle surfaces.

Chronic exposure to mineral dusts, especially those containing crystalline silica, is of concern due to the risk of diseases such as silicosis and cancer, which are observed in workers in dusty occupations. The La Palma magma has a low-silica tephritic composition, with no petrographic evidence for crystalline silica phases (Pankhurst et al., Preprint). Such eruptions generally do not to generate crystalline silica, so its presence was not tested.

The methods used to characterise the ash are part of the [IVHHN protocols](#) for rapid respiratory health hazard assessment of volcanic ash and leachate analysis. A number of previous studies have utilised these protocols, allowing comparison among the La Palma samples and eruptions elsewhere (Damby et al., 2013; Damby et al., 2017; Hillman et al., 2012; Horwell et al., 2013; Horwell et al., 2010a; Horwell et al., 2010b; Le Blond et al., 2010). The methods are described in further detail in these papers.

#### Methods

IVHHN received 37 samples of volcanic ash, collected on La Palma between 19 September - 16 October by co-authors MP, ST, and EL. The finest-grained 16 samples (by eye) were chosen for detailed analysis (Table 1, Figure 1).

**Table 1.** Ash sample information.

Ash sample	Collected by (organisation)	Location of collection	Date of collection	Period of collection	Further information
LP_21_ST_01	CUNY*	28.714340, -17.746905	26/09/2021	12-24 hours	Whole deposit sampled from concrete surface. Contaminated with cat hair. Dry.



The ash was sent to the UK where it was prepared (in Durham University, UK, laboratories) by weighing the samples and drying any damp samples overnight in an oven at 70 °C (these samples were then not used for leachate analysis). The samples were then sieved to > 2 mm, 1-2 mm and < 1 mm and each fraction weighed. The < 1 mm fraction was used for all subsequent analyses. This is to prevent damage of the laser diffraction granulometer used to determine particle size distribution and aligns with previous implementations of the IVHHN protocol. Each ash sample was mixed well, and splits used for the analyses listed in Table 2.

**Table 2.** Summary of analyses performed on ash samples.

Ash sample	Particle size	Morphology	Leachate <sup>a</sup>
LP_21_ST_01	x		x
LP_21_ST_02	x		x
LP_21_ST_03	x		x
LP_21_ST_04	x	x	x
LP_21_ST_11	x	x	x <sup>b</sup>
LP_21_ST_13			x
LP_21_ST_14	x	x	x
LP_21_ST_15			x
LP_21_IV_01	x	x	x <sup>b</sup>
LP_21_IV_02	x	x	x
LP_21_IV_03	x		
LP_21_IV_05	x		x
LP_21_IV_08	x		x
LP_21_EL_02	x	x	x <sup>b</sup>
LP_21_EL_08	x		
LP_21_EL_10	x	x	x

<sup>a</sup> leached in water for 1 hour at 1:20 and 1:100 (reported in Part 2)

<sup>b</sup> samples also leached in water for 24 hours at 1:100 (Part 1) and in 0.032 M HCl for 1 hour at 1:100 (Part 2)

**Particle size distribution:** Samples were analysed on a Beckman Coulter LS13 320 Particle Size Analyser (laser diffraction granulometer) at Durham University, using an optical model applying Mie theory to raw data (using a refractive index of 1.333 for water, 1.55 for the ash (based on the tephritic magma type; Horwell, 2007) and an adsorption coefficient of 0.1) and Polarization Intensity Differential Scattering (PIDS) technology. Each sample was introduced to a fluid module, containing water, until nominal obscuration (5-7%) and PIDS (40-60%) values were achieved. Acceptable obscuration could not be achieved for samples LP\_21\_ST\_13 & 15 so data are not included. Sonication was applied for 20 seconds and a wait time of 10 seconds prior to data acquisition, where run time was 90 seconds, and 3 runs were performed. An average of these 3 runs was produced to yield the data. As volcanic ash is defined as particles < 2 mm diameter, a calculation was performed to add the mass of the 1-2 mm fraction which was not introduced to the instrument.

**Particle morphology:** Ash was sprinkled onto polycarbonate discs which were stuck to carbon sticky pads on aluminium stubs, using a dry cotton bud. The stubs were coated with 10 nm gold to prevent charging of particles. Scanning Electron Microscope (SEM) imaging with Energy Dispersive Spectroscopy (EDS) analyses was conducted at the U.S. Geological Survey using a Tescan Vega3 SEM equipped with 2 Oxford Instruments X-Max<sup>N</sup> 150 mm<sup>2</sup> energy dispersive X-ray spectrometers. Imaging and analysis were conducted at 15 kV, with a working distance of 15 mm. When fibre-like particles were identified (aspect ratio of > 3:1; World Health Organization, 1997), EDS spot analyses were conducted to identify the composition of the particles. Samples were prioritized for imaging according to grain size (finest samples) and leachate data (highest concentrations).

**Leachate analyses for ash inhalation hazard:** Ash samples were leached for 24 hours using deionised water, at a ratio of 1 g ash to 100 mL extractant at the U.S. Geological Survey. These data serve as a conservative

proxy for leaching with physiologically realistic simulated lung fluid (Tomašek et al., 2021) and complement the 1 hour contact time recommended in the IVHHN protocol for assessing hazards from leachable elements (Stewart et al., 2020) (see Part 2 of this report). Concentrations of leached anions and cations were quantified using ion chromatography (IC; Dionex ICS-2000 with an AS-18 column) and inductively coupled plasma optical emission spectrometry (ICP-OES; ThermoFisher ICAP 6500 Duo), respectively. The pH and specific conductance of leachates were also measured. Leachate data are presented as milligrams of the leachable element per kilogram of ash (mg/kg). Sample data are blank-subtracted, and data rounded to reflect precision.

## Results

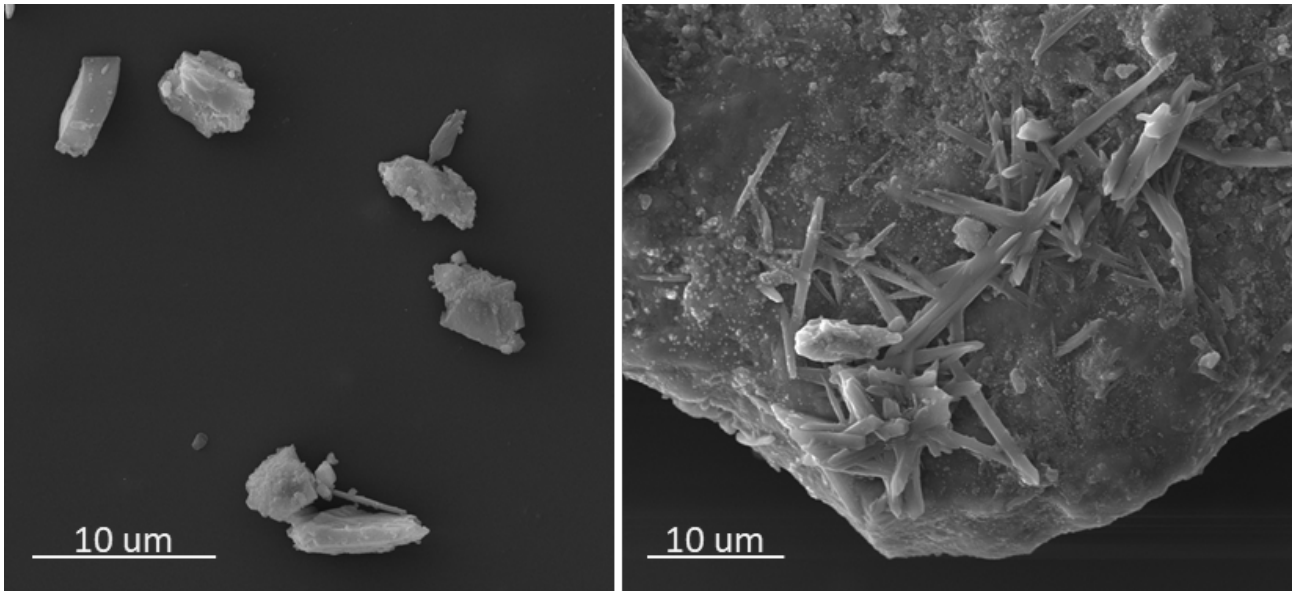
**Particle size distribution:** The data in Table 3 show the cumulative amount of material (measured in volume %) less than each of the particle size thresholds given, which relate to PM<sub>1</sub>, 2.5, 4, 10 & 100 (the particulate matter (PM) fractions of respiratory importance). The amount of respirable (< 4 µm diameter; able to efficiently reach the alveoli), thoracic (< 10 µm diameter; the fraction able to penetrate beyond the larynx) and inhalable (< 100 µm diameter; the fraction inhaled through the nose/mouth) material in the ash are typical of mildly explosive eruptions (Horwell, 2007). All samples contained < 1 vol.% respirable (< 4 µm) and thoracic (< 10 µm) material. The finest samples were collected from eruptions on 19 and 28 September and 14 October (where 6.6-15.5 vol.% of the ash was inhalable (< 100 µm)).

**Table 3.** Particle size results in cumulative vol.%.

Size fraction (< µm)	1.0	2.5	4.0	10.0	100.0
LP_21_ST_01	0.1	0.2	0.3	0.6	1.6
LP_21_ST_02	0.1	0.1	0.2	0.3	1.0
LP_21_ST_03	0.1	0.1	0.1	0.3	1.0
LP_21_ST_04	0.2	0.4	0.5	0.8	10.3
LP_21_ST_11	0.1	0.1	0.2	0.3	1.3
LP_21_ST_14	0.2	0.3	0.4	0.7	15.5
LP_21_IV_01	0.2	0.3	0.4	0.8	6.6
LP_21_IV_02	0.0	0.0	0.1	0.1	0.6
LP_21_IV_03	0.1	0.2	0.3	0.5	6.0
LP_21_IV_05	0.1	0.1	0.2	0.3	3.1
LP_21_IV_08	0.1	0.1	0.2	0.4	1.2
LP_21_EL_02	0.1	0.2	0.3	0.6	2.6
LP_21_EL_08	0.1	0.1	0.2	0.4	2.6
LP_21_EL_10	0.1	0.1	0.1	0.3	1.0

**Particle morphology:** SEM imaging (Figure 2) showed that thoracic (< 10 µm) and respirable (< 4 µm) ash particles were angular to sub-rounded, with finer particles often adhered to larger particles. This morphology is typical of ash particles of this size (e.g., Horwell et al., 2013; Horwell et al., 2010b). Fibre-like particles were observed in some samples, which we confirmed to be calcium sulphate (gypsum or anhydrite), volcanic glass and an unidentified silicate that does not appear to be related to asbestos. Precipitates are visible on ash surfaces.

**Leachate analysis:** Water-extractable concentrations in the three samples leached at 1:100 for 24 hours are highly variable but are generally low in comparison to ash analysed by the same methods from the 2018 eruption of Ambae volcano, Vanuatu, the 2018 eruption of Kilauea volcano, Hawaii, and the 2016 eruption of Whakaari/White Island volcano, New Zealand (Tomašek et al., 2021) (Table 4). There is generally good agreement of 24-hour leachate data with the 1-hour leachate results reported in Part 2, except for zinc, which is substantially lower in the 24-hour leach. This suggests that the 1-hour data serve as a good approximation for the respiratory leachate hazard in this suite of samples. Results suggest that exposure to high concentrations of the measured potentially toxic elements (Table 4) is likely to be low.



**Figure 2.** Left image: Representative scanning electron microscope (SEM) image. Ash particles in the thoracic fraction (< 10 µm) are mostly blocky and angular to sub-rounded in shape (image from sample LP\_21\_ST\_14). Note a high aspect ratio particle in the bottom centre of image). Right image: Fibre-like calcium sulfate crystals growing on the surface of an ash grain (sample LP\_21\_EL\_02). Other precipitates are also visible on the grain surface. Scale bars are depicted on images.

**Table 4.** Water-extractable concentrations (at 1:100 after 24 h) of potentially toxic elements (in mg/kg ash). Comparative data from Tomašek et al. (2021) for three recent eruptions are shown alongside. bdl = below detection limit.

	Cumbre Vieja samples			Comparative samples		
	LP_21_IV_01	LP_21_ST_11	LP_21_EL_02	Whakaari	Ambae	Kīlauea
Al	774	67.1	38.6	3018	72.8	229.2
Cd	< 0.1	< 0.1	< 0.1	0.08	0.02	0.04
Co	0.263	< 0.1	0.249	10.6	0.66	2.88
Cr	< 0.1	< 0.1	< 0.1	4.2	bdl	0.06
Fe	1.05	< 0.3	7.29	818.6	4.0	1420
Mn	22.2	1.83	2.19	83.2	31.1	95.4
Ni	0.154	0.141	0.177	20.4	2.6	9.1
Zn	1.03	0.483	1.05	10.2	2.2	4.7
Br	24.1	2.0	41			
Cl	1220	154	1240			
F	1790	358	243			
SO <sub>4</sub>	331	197	887			

## Discussion

When compared to ash analysed from other eruptions (e.g., Horwell, 2007 and the papers mentioned at the end of the Introduction), the freshly erupted ash has insufficient fine-grained material to be of respiratory concern. However, exposure to inhalable ash may still occur after deposition, due to fragmentation by natural and anthropogenic remobilisation processes (especially vehicles and wind). Further, any changes in the eruption mechanism of this ongoing eruption could affect the fragmentation mechanisms, influencing particle size distributions. Thus, airborne particulate concentrations should be monitored, and further analyses should be conducted of ash that is considered to be derived from more explosive phases. It should also be noted that this study did not analyse the hazard of volcanic gas and aerosol or 'laze', produced from

entry of lava into the ocean, which also have the potential to cause health impacts. Information on these hazards can be found at <https://www.ivhhn.org/information/health-impacts-volcanic-gases>.

There are few fibre-like particles in the ash and none of a concerning composition. Whilst some particles are described as angular, particles of this size are not 'sharp' and will not lacerate the lungs. The generally low concentrations of soluble potentially toxic elements also point to low respiratory risk.

The caveat with these findings is that ash particles will be remobilized into the air during dry periods, via clean-up activities, vehicles, agricultural activities, and wind, until ash is completely removed and incorporated into the soil. The World Health Organization has concluded that both fine and coarse particulate matter (including crustal particulate) is capable of causing respiratory and cardiovascular morbidity and mortality, and is associated with a wide range of other health outcomes (World Health Organization, 2013). Therefore, efforts to reduce exposures should be made<sup>2</sup>, particularly for those in vulnerable groups, especially young children (who are low to the ground where highest particle concentrations occur, and also commonly play at ground level), as well as those who work in outdoor occupations, especially associated with clean-up operations. Personal exposure and airborne concentrations of particulate matter should be monitored to assess the ongoing health risk.

## Part 2

### Assessment of potential for contamination of water sources, and ingestion hazards for livestock

#### Background

Leachate analyses are carried out to determine the concentrations of readily available elements on fresh volcanic ash particle surfaces. Release of these elements can have both beneficial effects (such as adding plant growth nutrients to pasture) or harmful effects (such as fluorine toxicity to livestock). Here, we carried out both a deionised water leach and an acid leach (also known as a simple gastric leach) according to the [IVHHN leachate protocol](#) (Stewart et al., 2020).

The deionised water leach assesses the release of readily water-soluble compounds from ash particle surfaces. This is applicable for predicting composition changes in natural water sources, roof catchment rainwater tanks, and crop irrigation water. The simple gastric (SG) leach estimates the bioaccessible fraction (the fraction that is soluble in biological conditions, in this case in the digestive tract) of possible toxicants to livestock from ingested ash. Grazing animals consume ash if it coats forage, or if it coats the soil near forage plants. Humans, especially children playing at ground level, may also ingest ash in small quantities.

#### Methods

Water leaches were performed on fourteen samples (see Table 2) at ash to leachant ratios (g:mL) of 1:20 and 1:100 in deionized water for 1 hour. These two complementary ratios are recommended as, at the 1:100 ratio, some elements may be below detection limits and, at the 1:20 ratio, dissolution of some compounds may be incomplete due to saturation effects. One in every five samples was run in duplicate as part of data quality management. The SG leach was performed on a sub-set of three samples at 1:100 in 0.032 M hydrochloric acid (HCl, pH 1.5) for 1 hour. The concentrations of leached anions and cations were quantified at the U.S. Geological Survey using ion chromatography (IC) and inductively coupled plasma optical emission spectrometry (ICP-OES), respectively. Leachate data are presented as milligrams of the leachable component per kilogram of ash (mg/kg). The pH and specific conductance of water leachates are also reported.

#### Results and Discussion

Water leach: Water-extractable elements at 1:100 are shown in Table 5, with global median data (Ayris and Delmelle, 2012) shown alongside for comparison. Data at 1:20 are available as a separate spreadsheet upon request.

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<sup>2</sup> Information on community protection and exposure reduction measures is available at <https://www.ivhhn.org/information>

Consistently higher concentrations were measured at 1:100 for barium, magnesium, sodium, silicon (as SiO<sub>2</sub>) and zinc, indicating inhibited dissolution at the 1:20 ratio. Similarly, higher concentrations of aluminium were measured at 1:100 for samples with greater overall leachate concentrations (e.g., LP\_21\_IV\_01, 02 & 05), suggesting inhibited Al dissolution as the soluble salt cargo increased. Fluoride and sulfate are also consistently higher at 1:100. Conversely, potassium is consistently higher at 1:20 across all samples. For other elements, similar concentrations were reported in the 1:100 and the 1:20 leaches.

Fluoride, an element of primary concern for human and animal health, is higher than global median values in all samples, particularly those from early in the eruption (LP\_21\_IV\_01, 02 & 05; 762-1490 mg/kg). Though variable, concentrations appear to have plateaued (119-489 mg/kg) since early in the eruption but remain higher than global median values and are at levels that may be hazardous to open water resources. Also notable are high (relative to global median) concentrations of Zn and Ba. Concentrations of other elements are generally low in comparison to global values, with concentrations of Ca, Fe, K, Mg and Mn being notably low. Pb and Hg were not measured.

Local response efforts should be informed by direct analysis of both raw water sources and treated drinking water, where possible (see IVHHN briefing note about post-ashfall water quality management: <https://www.ivhhn.org/crisis-management>).

Simple gastric leach: Concentrations of elements leached by the SG extractant are shown in Table 6. The SG leach extracted greater quantities of almost all elements than the water leach, consistent with observations from other eruptions (Cronin et al., 2014). Tenfold or greater quantities were released using SG relative to water leaching for Al, Cr, Fe, Ni, PO<sub>4</sub> and SiO<sub>2</sub>, and approximately tenfold increases for As and B. Smaller increases in the concentrations of PTEs Mn and Zn were observed. There is an approximately twofold increase in F observed in the SG leachate for sample LP-21-IV-01, indicating an increase in availability of F as a result of ash ingestion.

In most cases, the physical effects (tooth abrasion, irritant effects, intestinal blockages) of ash ingestion by grazing livestock dominate over toxicological impacts from elements leached from ash surfaces. Poisoning of livestock is associated primarily with high fluoride on ash and, in some cases, very high concentrations of sulfur (see Appendix 1). Very rarely, problems may arise from high concentrations of zinc (measured to be high) or copper (not measured). For the ash samples analysed here, concentrations of some SG-extractable toxicants are noteworthy. There are no established thresholds in mg F per kg ash because there are other critical variables for determining exposure, such as ashfall thickness and type of feeding (see Appendix 1). However, fluoride toxicity has been observed elsewhere at similar or lower F concentrations than those measured in these samples (Cronin et al., 2003; Cronin et al., 2014; Stewart et al., 2016; Stewart et al., 2020). To further investigate livestock health hazard, examination of farming practices, feeds and other factors are needed (species, ingestion rates, water intake, etc.). The results suggest that immediate practical mitigation of a possible F hazard would be to provide supplementary feed for animals. To reduce human exposures, ash should be washed off the surface of locally grown fruit or vegetables before eating.

Additional general information about ash impacts on animal health is provided in Appendix 1.

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**Table 5.** pH, conductivity ( $\mu\text{S}/\text{cm}$ ) and water-extractable elements (in  $\text{mg}/\text{kg}$  ash) at 1:100 for 1 hour.

Ash sample	LP_21_ ST_01	LP_21_ ST_02	LP_21_ ST_03	LP_21_ ST_04	LP_21_ ST_11	LP_21_ ST_13	LP_21_ ST_14	LP_21_ ST_15	LP_21_I V_01	LP_21_I V_02	LP_21_I V_05	LP_21_I V_08	LP_21_ EL_02	LP_21_ EL_10	Global median concentrations*
<b>pH</b>	5.58	5.82	5.58	5.80		5.61	5.32	5.60	4.50	4.91	5.44	5.55	5.44	5.34	
<b>Conductivity</b>	34.40	33.99	38.40	57.17	50.04	37.86	62.63	61.29	100.40	53.27	67.83	38.04	99.19	27.17	
<b>Al</b>	1.18	3.07	26.7	3.87	55.4	16.7	66.4	19.8	479	162	203	1.45	26.9	4.27	58
<b>As</b>	0.13	< 0.1	0.11	< 0.1	0.12	< 0.1	0.03	0.06	< 0.1	< 0.1	< 0.1	< 0.1	0.12	< 0.1	0.13
<b>B</b>	2.5	2.7	2.8	1.8	3.4	6.80	6.30	6.20	3.7	3.6	3	3.3	3.5	3.6	2.6
<b>Ba</b>	11.5	12.3	16.7	16	16.8	23.50	22.40	20.00	19.5	18.9	18.4	11.7	15.2	11.4	0.94
<b>Br</b>	7	3	3	1.72	< 1	2.0	< 1	< 1	11.4	0.68	< 0.2	0.66	33	7	1.9
<b>Ca</b>	104	93.9	200	523	204	123	227	190	643	269	344	85.9	316	75.9	2140
<b>Cd</b>	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.053
<b>Cl</b>	14	59	57	40.7	188	106	254	78	1350	320	537	67.1	1270	39	1162
<b>Co</b>	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.282	< 0.1	< 0.1	< 0.1	0.237	< 0.1	0.186
<b>Cr</b>	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.096
<b>F</b>	119	160	386	331	474	309	489	341	1490	762	773	175	299	170	129
<b>Fe</b>	< 0.3	< 0.3	< 0.3	0.7	< 0.3	< 0.3	< 0.3	< 0.3	0.7	1.1	< 0.3	< 0.3	7.6	< 0.3	21
<b>K</b>	1.8	2.4	7.3	< 1	30.4	20.2	56	51.6	129	25.6	53.1	6.4	146	0.9	71
<b>Li</b>	< 0.1	0.119	< 0.1	< 0.1	0.119	< 0.1	< 0.1	< 0.1	< 0.1	0.11	0.166	< 0.1	< 0.1	< 0.1	0.22
<b>Mg</b>	13.8	20.3	31.9	32.7	43.3	34.8	42.2	22.3	122	76.4	90.5	13.6	101	12.3	335
<b>Mn</b>	0.44	0.65	1.19	0.35	2.01	1.44	2.18	0.768	24.2	5.54	7.14	0.46	2.10	0.35	20
<b>Mo</b>	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.063
<b>Na</b>	295	242	273	245	462	320	637	737	584	367	490	344	1150	239	378
<b>Ni</b>	0.11	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.171	< 0.1	0.20	< 0.1	0.22	0.26	< 0.1	< 0.1	0.50
<b>NO<sub>3</sub></b>	1.0	1.0	2.0	< 1	2.4	2.0	2.0	2.0	1.3	25.4	50.0	5.3	3.0	3.0	22
<b>PO<sub>4</sub></b>	4.0	4.0	4.0	4.6	2.5	< 1	< 1	1.0	0.3	1.7	2.0	3.0	3.0	4.0	227
<b>Rb</b>	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	0.083
<b>Se</b>	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	0.055
<b>SiO<sub>2</sub></b>	33	26.1	24.5	28.5	36.3	< 10	10.2	16.9	28.9	15.4	14.8	33.6	29.5	24.1	54
<b>SO<sub>4</sub></b>	443	309	310	395	599	342	1060	1430	648	283	468	588	1250	298	4986
<b>Sr</b>	2.05	1.52	2.95	5.43	4.18	2.03	4.96	5.39	10.5	4.28	6.08	1.91	5.52	1.37	4.3
<b>Zn</b>	< 1	4.9	19.1	< 1	19.0	27.7	33.5	28.8	23.6	21.4	21.4	< 1	20.8	7.4	3.6

\*Global median concentration values from Ayris & Delmelle (2012)

**Table 6.** HCl-extractable elements (simple gastric leach at pH1.5; in mg/kg ash) for samples at 1:100 for 1 hour. Water data are from Table 5.

Ash Sample	LP_21_IV_01		LP_21_ST_11		LP_21_EL_02	
	Gastric	Water	Gastric	Water	Gastric	Water
Al	2570	479	917	55.4	1130	26.9
As	0.92	< 0.1	0.94	0.12	1.23	0.12
B	30.80	3.7	28.60	3.4	26.80	3.5
Ba	77.50	19.5	70.40	16.8	56.90	15.2
Br	39.1	11.4	8.94	< 1	19.0	33
Ca	1750	643	763	204	855	316
Cd	< 1	< 0.1	< 1	< 0.1	< 1	< 0.1
Co	< 1	0.282	< 1	< 0.1	< 1	0.237
Cr	5.25	< 0.1	5.46	< 0.1	5.14	< 0.1
F	2690	1490	482	474	325	299
Fe	507.0	0.7	529.0	< 0.3	350.0	7.6
K	473	129	349	30.4	486	146
Li	< 1	< 0.1	< 1	0.119	< 1	< 0.1
Mg	334	122	176	43.3	186	101
Mn	40.1	24.2	12.7	2.01	9.48	2.10
Mo	< 1	< 0.1	< 1	< 0.1	< 1	< 0.1
Na	1310	584	1120	462	2060	1150
Ni	2.95	0.20	2.76	< 0.1	2.85	< 0.1
NO <sub>3</sub>	< 5	1.3	< 4	2.4	< 4	3.0
PO <sub>4</sub>	183	0.3	107	2.5	128	3.0
Rb	<10	< 1	< 10	< 1	< 10	< 1
Se	< 5	< 0.5	< 5	< 0.5	< 5	< 0.5
SiO <sub>2</sub>	1790	28.9	2080	36.3	2550	29.5
SO <sub>4</sub>	1200	648	1290	599	2100	1250
Sr	31.8	10.5	17.0	4.18	18.9	5.52
Zn	60.8	23.6	58.4	19.0	56.0	20.8

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## APPENDIX 1: Volcanic ash impacts on animal health

Volcanic ash affects animals by causing: (1) starvation and dehydration, (2) respiratory problems, (3) eye problems, (4) digestion/gastric problems, (5) stress, and, in some cases, (6) poisoning by toxic agents that may result in fatality.

1. Ashfalls can smother feed and animals can succumb to starvation (inanition) if supplementary feed is not provided. Ashfalls can also block or restrict access to water sources, leading to dehydration. In addition, ingesting ash-covered feed can cause accelerated wear of teeth which can further impair feeding.
2. Respiratory problems are typically associated with long-period exposure to fine-grained ash, especially if it is re-suspended in dry, dusty climates.
3. Eyes are very vulnerable to fine airborne ash particles. Common eye injuries include abrasion of the cornea, irritation, and conjunctivitis.
4. Gastric problems can be caused by ingested ash acting as a physical irritant, especially if it is acidic. Animals ingesting large quantities of ash along with feed can also suffer intestinal blockages.
5. Stress can be generated by the changed environmental conditions and the unpalatability of feed for grazing animals. Acidic ash is pungent and reduces palatability of forage, leading to loss of condition or starvation.
6. Poisoning is associated primarily with high fluorine in volcanic ash and, in some cases, very high concentrations of sulfur. In other, very rare cases, volcanic ash may contain high concentrations of potentially toxic metals such as copper or zinc.

Thickness of ashfall	Potential consequences
Thin falls (1-10 mm)	<p><u>Livestock:</u> Effects on livestock expected to be minor and may include irritation of eyes and skin. Animals may ingest ash along with feed but small quantities are unlikely to cause harm. Cases of fluorosis are rare but have been reported for these quantities of ashfall, for ash containing moderate to high levels of bioaccessible F.</p> <p><u>Crops and soils:</u> Impacts of thin ashfalls on crops depend strongly on seasonality (with effects less severe during the wet season) and crop type, and include acid damage to foliage (which can in turn lower disease resistance), partial smothering inhibiting photosynthesis and crop spoilage. Effects of thin ashfalls on soils are complex and depend on both ash and soil characteristics. Ash may produce a beneficial mulching effect and may also add beneficial amounts of agronomically useful elements.</p>
Moderate falls (10-100 mm)	<p><u>Livestock:</u> As for thin falls, thicker falls may smother feed and restrict access to drinking water, leading to starvation and/or dehydration. Ingestion of larger quantities of ash may cause intestinal blockages. Livestock may require supplementary feed due to ash coverage of pasture. Cases of fluorosis more probable.</p> <p><u>Crops and soils:</u> As for thin falls, effects of loading damage and shading from light become more prevalent for crops. Thicker falls will have increasingly detrimental effects on soils as loading increases and the 'ash blanket' disrupts key soil processes.</p>
Thick falls (> 100 mm)	Burial of pasture and most crops; loading damage to tree crops likely. Soil rehabilitation, through removal or mixing in of the ash, is typically required for agricultural production to be restored. The fertility of buried soil may wane over time as key soil processes (e.g., nitrogen and oxygen cycles) are disrupted. Farm assets such as irrigation systems and access ways likely to be damaged or buried. Tree damage possible in production forests.

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