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REGULAR ARTICLE

Recovery after volcanic ash deposition: vegetation effects on soil organic carbon, soil structure and infiltration rates

Danny Dwi Saputra · Rika Ratna Sari · Kurniatun Hairiah · Widianto · Didik Suprayogo · Meine van Noordwijk

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Abstract

Background and purpose Volcanic eruptions of pyroclastic tephra, including the ash-sized fraction (<2 mm; referred to as volcanic ash), have negative direct impacts on soil quality. The intensity (deposit thickness, particle-size distribution) and frequency (return period) of tephra deposition influence soil formation. Vulnerability and subsequent recovery (resilience) of the plant-soil system depend on land-uses (vegetation and management). Few previous studies covered the whole deposition-recovery cycle. We investigated the volcanic ash deposition effects on soil properties and their recovery across land-uses on a densely populated volcanic slope.

Methods We measured the canopy cover and volcanic ash thickness six years after the 2014 Mt. Kelud eruption in four land-use systems: remnant (degraded) forests, complex agroforestry, simple agroforestry, and annual crops. Each system was monitored in three landscape replicates (total 12 plots). For the soil recovery study, we measured litter thickness, soil texture, C_{org}, soil C stocks, aggregate stability, porosity, and soil infiltration in three different observation periods (pre-eruption, three, and six years after eruption).

Results Post-eruption volcanic ash thickness varied between land-use systems and was influenced by the plots slope position rather than canopy cover. The average soil texture and porosity did not vary significantly between the periods. Surface volcanic ash and soil layers initially had low aggregate stability and limited soil infiltration, demonstrating hydrophobicity. While C_{org} slowly increased from low levels in the fresh volcanic ash, surface litter layer, aggregate stability, and soil infiltration quickly recovered.

Conclusions Different land-use management resulted in different recovery trajectories of soil physical properties and function over the medium to long term after volcanic ash deposition.

Keywords Volcanic eruption · Resilience · Agroforestry · Hydrophobicity · Soil quality · Soil degradation · Soil restoration · Tephra

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D. Saputra (✉) · R. Sari · M. van Noordwijk
Plant Production System, Department of Plant Sciences, Wageningen University and Research, P.O. Box 430, 6700 AK Wageningen, The Netherlands
e-mail: dannydwi.saputra@wur.nl; danny_saputra@ub.ac.id

D. Saputra · R. Sari · K. Hairiah · Widianto · D. Suprayogo
Department of Soil Science and Forestry, Faculty of Agriculture, Brawijaya University, Jalan Veteran 65145, Malang, Indonesia

M. van Noordwijk
World Agroforestry, ICRAF Southeast Asia, Bogor, Indonesia

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Abbreviations

CAF	Complex coffee-based agroforestry
C_{org}	Soil organic carbon
CR	Annual crops
DF	Remnant (degraded) forest
LUS	Land-use systems
m a.s.l	Meter above-sea-level
MWD	Mean weight diameter
SAF	Simple coffee-based agroforestry
YAE	Year after eruption

Introduction

Volcanic soils have extraordinarily high soil fertility once ash deposited on the surface has become soil with Andic properties (Sanchez 2019). However, farming on volcanic slopes and adjacent valleys also involves exposure to extreme circumstances during volcanic eruptions. This includes pyroclastic materials deposition of < 2 mm tephra fractions (it includes sand, silt and clay particles in conventional texture analysis) which is often directly referred to as 'volcanic ash' (Arnalds 2013; Fuentes et al. 2020; Müller et al. 2019; Rossi et al. 2021; Suh et al. 2019), and subsequent volcanic ash movement in the landscape (Anda et al. 2016; Ayris and Delmelle 2012; Zobel and Antos 2017). Parts of the literature on volcanic soils describes long-term soil genesis (Babiera and Takahashi 1997; Dahlgren and Ugolini 1989; Fiantis et al. 2021; Fiantis et al. 2017; James et al. 2016; Ontiveros et al. 2016; Schlesinger et al. 1998). Other authors have a focus on the short-to-medium term consequences for vegetation dynamics (del Moral and Lacher 2005; Magnin et al. 2017; Swanson et al. 2016; Zobel and Antos 2017), the hydrological characteristics and sedimentation in the drainage basin (Hendrayanto et al. 1995; Leavesley et al. 1989; Major et al. 2009; Manville et al. 2009; Pierson and Major 2014), or soil development and biological communities (Fernández et al. 2018; Ferreiro et al. 2018; Fiantis et al. 2019; Fiantis et al. 2016; Tateno et al. 2019; Yamanaka and Okabe 2006). However, few studies have described the extensive short-medium-long term changes and recovery of soil physical characteristics and functions.

Indonesia has the largest number of active volcanoes on earth (Nihayatul et al. 2017), and nearly all are densely populated. Six out of ten of the most populous active volcanoes in the world are located in Indonesia (Small and Naumann 2001). Among them is Mt. Kelud (also known as Kelut) in East Java, which had a human population density of more than 800 km^{-2} in 2020. Mt. Kelud has erupted more than 30 times since 1000 AD (Nawiyanto and Nurhadi. 2019), including the most recent significant eruptions in 1990 and 2014 (Goode et al. 2019; Maeno et al. 2019; Nakada et al. 2016).

The severity and variety impacts of volcanic materials depositions depend on the intensity metrics (tephra characteristics, such as layer thickness and grain size) and vulnerability of the exposed land-use system(s) (Arnalds 2013; Craig et al. 2016). Differences in vegetation structure (stem and leaf architecture, height and density) may influence the amount of volcanic ash captured, but will certainly affect the volcanic ash layer thickness retained on the soil profile (Cutler et al. 2016). A tree canopy or a shrub is expected to locally modify air turbulence, and capture and retain a portion of the air-borne volcanic ash (Ayris and Delmelle 2012). This volcanic ash is subsequently transferred to the ground as leaves drop or wind and rain mobilize the ash out of the canopy (Swanson et al. 2013). Dugmore et al. (2018) found that tephra layers developed underneath tall shrubs were 36% thicker than the original fallout when evenly distributed. This implies that tree-based systems may be more susceptible to change its soil properties due to thicker tephra deposits compared to monoculture crop systems.

Tephra interception by tree canopies may lead to leaf abrasion and/or induce litterfall (Ayris and Delmelle 2012; Korup et al. 2019; Swanson et al. 2013). Changes in soil characteristics following volcanic events may have a substantial effect on plant establishment and development (Fernández et al. 2018). Tephra deposits on soil surface may change soil structure (Blong et al. 2017) and impede water infiltration, a characteristic sometimes described as hydrophobicity (Anda et al. 2016; Hairiah et al. 2016; Pierson and Major 2014). However, plant growth will eventually recover with time, and new soil will develop simultaneously. A conceptual diagram of volcanic ash deposition and its aftermath (Fig. 1) describes a typical sequence of processes as:

1. Volcanic eruption ejects tephra (including volcanic ash) into the atmosphere, deposited on

forests and agricultural land, depending on the height of the eruption plume, wind direction, wind speed. The deposition pattern is potentially modified by the surface roughness of the vegetation and its turbulence effects.

2. Volcanic ash causes direct and indirect damage to trees-some trees survive, others die due to the loss of canopy and/or leaf abrasion from the heavy ash load.
3. Volcanic ash and fresh litter partially or fully cover the original soil. After interacting with rainwater, ash may be redistributed downhill and/or quickly become compacted due to the lower aggregate stability and porosity. This compacted layer (crust) can temporarily disconnect the underlying soil from the atmosphere.
4. The disconnection may disrupt the water and nutrient balance in the soil due to lower soil infiltration and aeration, including inhibition of soil organic matter decomposition and mineralisation.
5. Severely damaged leaves combined with low soil nutrient and water availability reduce tree photosynthesis, and lead to low production during the early years post volcanic event, as trees may skip flowering and fruiting.
6. To improve the soil condition after the eruption, some farmers mixed the volcanic ash and fresh litter with the original soil and added inorganic fertilizer and organic matter (from manure).
7. Mixing fresh volcanic ash, litter and manure with original soil increases soil organic matter content and triggers higher soil organism activities (bioturbation). This process may improve the soil structure as indicated by a higher soil aggregate stability and macroporosity, thus improving the water and nutrient balances.
8. Weathered volcanic ash starts to provide nutrients for plants.
9. A better nutrient and water balance in the soil accelerates the recovery of the trees that survived immediate impacts and/or the growth of the newly established or planted trees.
10. Trees that are recovered and/or newly planted consistently begin to produce litter and contribute to the further accumulation of soil organic matter. Higher soil organic matter contents may increase the presence and activity of soil biota, thus improving soil structure and increasing the availability of water and nutrients. This favourable condition may further accelerate soil development and recovery of the land-use system – until the next disturbance restarts the cycle.

The rate of ecosystem recovery post-eruption depends on the interrelation between volcanic ash characteristics and environmental factors, including climate, the resilience of the ecosystem and farmer management. Ferreiro et al. (2018) showed that two years post-eruption, the forests tephra accumulated more biomass and litter than bare tephra, accelerating the invertebrate and microbial development. The development of biological activity in fresh volcanic ash layers may enhance the soil organic carbon and nitrogen availability, positively affecting plant growth (Fiantis et al. 2019). On the other hand, human intervention after volcanic events in agricultural systems such as replanting trees, adding organic matter, and incorporating volcanic ash with original soil may contribute to ecosystem recovery (Craig et al. 2016; Ishaq et al. 2020; Sword-Daniels et al. 2011; Wilson et al. 2011).

The timeframe for ecosystem recovery depends on volcanic ash thickness: decades necessary for thin, centuries for moderate, and millennia for very thick layers (Arnalds 2013). However, the knowledge on change in soil characteristics and soil functions in natural and agricultural ecosystems has not been well developed, as most studies only cover limited phases of the eruption-recovery cycle. In addition, the next disturbance may come earlier before recovery of the system is achieved, particularly for the locations with frequent volcanic ash deposition.

The general aims of this study were (1) to provide an assessment of the volcanic ash thickness in natural and agricultural land-use systems and (2) to explore the resilience of natural and agricultural systems after volcanic ash deposition by investigating the litter thickness, and soil physical characteristics and function in relation to vegetation development and system recovery. Our research opportunity arose when Mt. Kelud erupted in February 2014 and precipitated up to 20 cm of volcanic ash in the Ngantang sub regency, East Java (Nakada et al. 2016). This eruption affected existing long-term research plots established in 2007 in a landscape mosaic with degraded forests, coffee and fruit tree agroforestry, and open field vegetable production. We resampled these plots after the

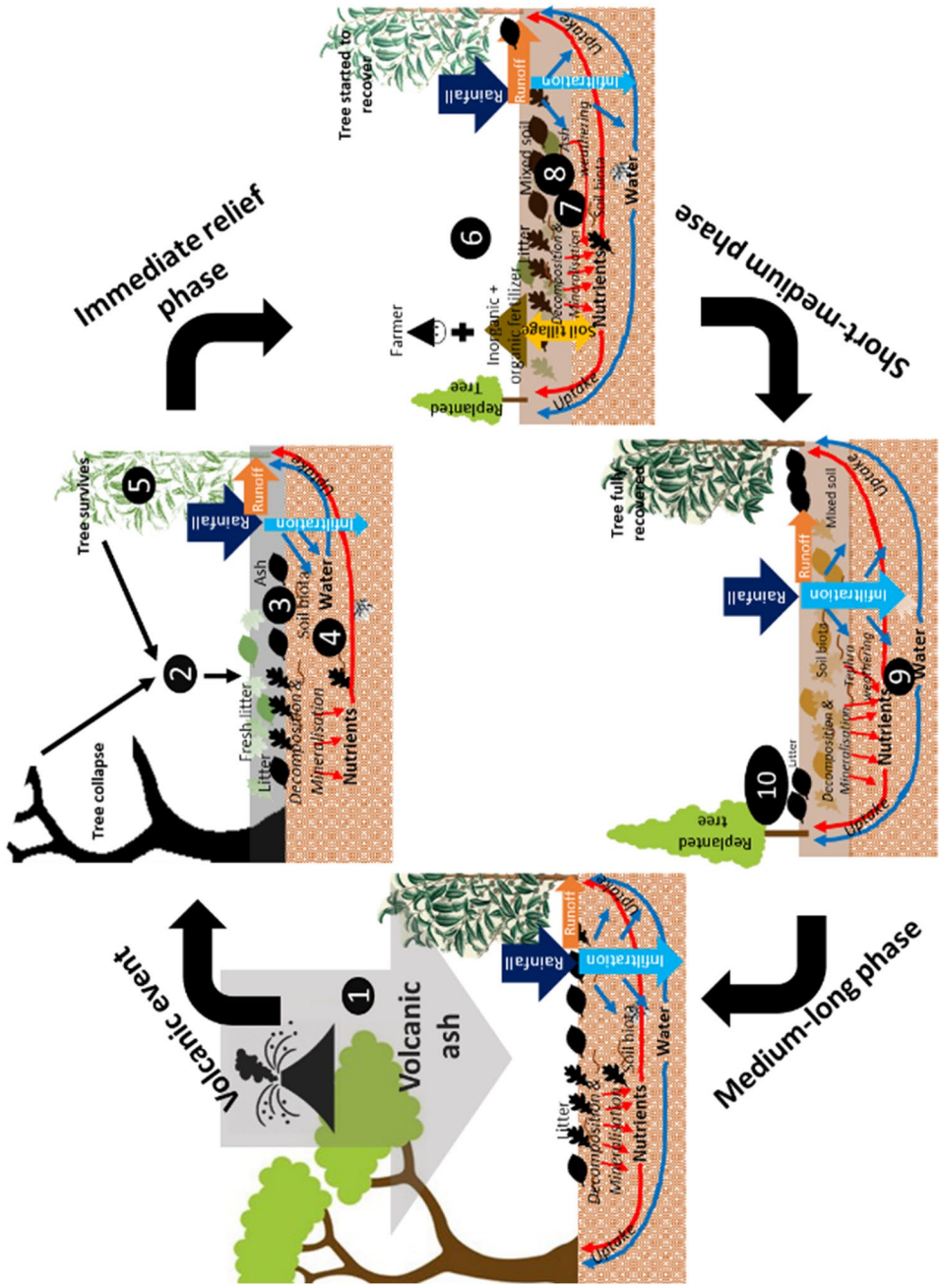


Fig. 1 The conceptual diagram on volcanic ash deposition impacts on plant and soil development in the tree-based system; processes 1–10 are described in the text

immediate relief phase of three and six years after the 2014 eruption, allowing us to monitor the changes in vegetation and soil characteristics, and to explore the local ecological knowledge and farmer decisions in response to the event. We will focus on the soil physical properties and soil function changes post volcanic ash deposition as consideration for farmer decisions to modify their land-use systems. In this study, we have three research questions:

1. Are there indications of any causal relation between canopy cover and volcanic ash thickness six years after the volcanic eruption?
2. Do the present land-use systems and farmer practices affect the recovery of litter thickness, soil organic carbon, soil structure, and soil infiltration after tephra deposition?
3. How does litter thickness in various land-use systems relate to soil organic carbon and recovery of infiltration rates?

We hypothesized that: (1) Canopy cover increases the volcanic ash thickness; (2) Tree-based land-use systems (forests and agroforestry) had a thicker litter layer, a higher soil organic carbon, a better soil structure, and higher water infiltration rates compared to annual crops; (3) Infiltration rates in tree-based systems were recovering faster than the annual crops. We expected that a more detailed understanding of soil changes in response to farmer management could contribute to the successful planning and implementation of restoration activities in the aftermath of future volcanic eruptions, based on the tree and soil management optimization.

Methods

Study area and research approach

This study took place in the Kalikonto Watershed (7°45′57"- 7°56′53"S and 112°19′18"- 112°29′57" E, with elevation ranging from 600–2800 m above-sea-level (m a.s.l.), located in Ngantang Sub-district, Malang Regency, Indonesia. The study area is 13–15 km north of Mt. Kelud (7°55′48″S—112°18′29″E) (Online resource 1). The Kalikonto watershed is characterized by a tropical monsoon climate, with a dry season from June to October and a rainy season from November to March. The annual rainfall varies from 2995 to 4422 mm year^{-1}, with the annual average temperature between 20°–22 °C, without much seasonality (BMKG 2018).

A 'chronosequence' of plots in four land-use systems with different degrees of change from the original natural forest cover was established in 2007/08 and resampled in 2016/17 and 2019/2020. Relative to the 2014 Mt. Kelud eruption, we labelled the 2007/08 data as 'pre-eruption (PRE)' condition. Meanwhile, the 2016/17 and 2019/20 datasets were labelled as '3 and 6 years after eruption (YAE)' respectively. Given the 24-years between the last major events (1990 – 2014), datasets also represent the short-medium (3 to 6 years) and long term (17 years) impacts of ash deposition.

Land-use systems

To test the hypotheses, we measured the soil physical properties of soil and volcanic ash (particles size < 2 mm) layer in four land-use systems (LUS): remnant (degraded) forests, coffee-based complex agroforestry system, coffee-based simple agroforestry system, and monoculture annual crops. Each land-use system included 3 plots on different locations, which can be considered landscape-level replications (total of 12 plots). A relative similar distance between the study site and the volcano implied that they probably received similar amounts of tephra with identical composition during the recent eruption (Cutler et al. 2016). All soils of these plots were classified as Inceptisols according to the USDA classification and Cambisols according to the FAO classification (Driessen et al. 2001).

Remnant (degraded) forests (DF)

The term remnant (degraded) forests as used in this article is based on the FAO definition: "changes within the forests which negatively affect the structure or function of the stand or site, and thereby lower capacity to supply products and/or services" (Schoene et al. 2007). Relatively open forests (but still having more than 10% of canopy cover that met the forest definition used by FAO) mainly resulted from human activities such as overexploitation of forest trees for timber or fuelwood. In the local context, degradation

implies a reduction of woody biomass, and changes in tree species composition, structure and productivity compared to natural forests expected for such climate and soil conditions. All DF plots were located at altitudes ranging from 900–1133 m a.s.l. with an average gradient of 40% at the lower slopes of local relief.

Coffee-based complex agroforestry (CAF) and simple agroforestry (SAF)

We used the relative basal area of the dominant tree crop and the number of companion tree species to differentiate between complex and simple agroforestry (Sari et al. 2020). Agroforestry systems combine cash crops and shade trees with a relative basal area of the main crop (coffee) of less than 80%; otherwise, they are described as 'monocultures'. Agroforestry systems with at least 5 tree species in a 20 m by 20 m plot were defined as complex agroforestry and those with 2–4 tree species as simple agroforestry (Hairiah et al. 2020). Relative coffee basal area was calculated for a standard 20 m by 20 m observation plot (Hairiah et al. 2006; Sari et al. 2020). CAF plots were mainly located on slopes with an altitude ranging from 750–950 m a.s.l., and an average gradient of 11%. SAF plots were found at similar elevations but further from the settlement on steeper terrain with an average gradient of 23%. Both CAF and SAF were situated in the middle part of the local relief. After the eruption, CAF and SAF farmers reportedly removed the volcanic ash near the tree trunk manually, and applied an organic (2.5–3.5 Mg ha^{-1} manure $year^{-1}$) and inorganic fertilisers (120 kg N, 30–60 kg P, and 30–60 kg K ha^{-1} $year^{-1}$). Important trees in farmer-managed agroforestry system include *Durio zibethinus ('durian')* as an indigenous fruit and timber tree, *Swietenia mahagoni ('mahogani'),* an introduced timber tree, and *Toona sureni* (*'suren'*), an indigenous timber tree.

Annual crops (CR)

CR plots were situated at a lower altitude than other LUS (673–761 m a.s.l.) with an average gradient of 2%. The main crops were napier grass (*Cenchrus purpureus*), maize (*Zea mays*), groundnut (*Arachis hypogea*), cabbage (*Brassica oleracea*), chilli pepper (*Capsicum annuum*), and upland rice (*Oryza sativa*). Land management mainly was intensive, with 2–3 planting cycles in a year. Soil tillage, fertilizer (organic and inorganic) application, weeding and pest control were associated with the planting cycles. After the eruption, some farmers mixed the soil and volcanic ash using a small hand tractor and applied organic (5.6 Mg ha^{-1} manure $year^{-1}$) and inorganic fertilisers (200 kg N, 120 kg P, 120 kg K ha^{-1} $year^{-1}$).

Data collection and statistical analysis

Canopy cover and volcanic ash thickness

We measured the canopy cover and 'preserved' volcanic ash thickness in the plots on October 2020 or six years after 2014's Mt. Kelud eruption (6 YAE). Three sampling points were placed on the diagonal of the plots for canopy cover and volcanic ash thickness measurements (Online resource 2). We split each sampling point into four sampling directions (based on the slope direction), with the coffee tree as a center point in CAF and SAF. Each direction was then divided into 30 cm length grids. Canopy cover was measured with an upward-facing photograph and the 'CanopyApp' in each grid, 30 cm above the soil level surface. This method was reported to show a strong and linear relationship ($R^2 = 0.87$) to canopy cover measurement using a spherical densitometer (Davis et al. 2019).

We exposed a cross-section of the volcanic ash and soil layers for the preserved ash thickness measurements by creating a shallow trench with a sharp spade (Dugmore et al. 2018). The trench was dug up underneath the canopy cover measurement points. We directly measured the volcanic ash thickness with a ruler perpendicular to the soil surface. The preserved volcanic ash layer was easily differentiated as it laid very close to the surface and showed a different colour and texture from the original soil underneath (Fig. 4c). For further statistical analysis, the canopy cover and volcanic ash thickness were averaged per plot.

The Mt. Kelud 2014 eruption is sufficiently recent that vegetation cover in tree-based systems has not changed dramatically. Therefore, we only included the data points from tree-based systems and excluded the CR data for the correlation analysis between canopy cover and volcanic ash thickness. However, we included data from all land-use

systems for the correlation analysis between slope position and volcanic ash thickness.

Litter thickness and soil parameters

We used the litter thickness to assess litter layer development (Marín-Castro et al. 2017). Standing litter thickness was measured using a ruler inside a 0.5 m × 0.5 m frame (Hairiah et al. 2006), placed on the same three diagonal points as the volcanic ash thickness measurement. Soil samples were collected from the upper 30 cm of the soil layer at three different periods (PRE, 3 YAE, and 6 YAE). This layer includes volcanic ash deposits and some parts of original soil material, that were mixed in naturally and/or anthropogenic ways.

The disturbed and undisturbed soil samples were collected from 2 sampling points near the litter measurement. We mixed the disturbed soil sample from two sampling points to create a composite sample. Composited soil samples were air-dried for 48 h and stored at room temperature (28 °C) before further analysis.

Soil and volcanic ash texture (% of sand, silt, and clay) was determined using the pipette method, while soil organic carbon (C_{org}) was determined using Walkley and Black method (Anderson and Ingram 1993). The top 30 cm of soil C stocks was calculated based on the IPCC guideline for national greenhouse gas inventories standard by multiplying soil C_{org} with the bulk density (Hairiah et al. 2011). Soil aggregate stability was measured through wet sieving methods and was represented as mean weight diameter (MWD, mm) (Carrizo et al. 2015). Soil porosity was calculated as Nimmo (2004): porosity (%) = 100 * (1 – bulk density/particle density). All soil samples were prepared and analysed in the Soil Science Laboratory of Brawijaya University.

Soil infiltration was measured using a single ring infiltrometer (Sahin et al. 2016). The infiltration rate was determined from two measurement points for each plot. The infiltration rate was expressed in water volume per ground surface and per unit of time (cm $hour^{-1}$). Steady-state infiltrability was afterwards estimated by mean of curve fitting to Horton's equation (Toebes 1962) using SigmaPlot 14.5 edition.

Statistical analysis

To assess the likely effect of land-use systems, we used a space-for-time substitution or chronosequence approach, checking for indications of a priori soil differences due to landscape position. We analysed data on canopy cover, volcanic ash thickness, litter thickness, and soil variables with a standard analysis of variance (ANOVA, $\alpha = 0.05$). *Post-hoc* multiple comparisons between LUS and observation periods were performed using Tukey's HSD (honestly significantly difference) test. Statistical differences were considered significant when $p \leq 0.05$. A Pearson correlation and stepwise linear regression were performed to investigate the relationships between variables. All statistical analysis was performed in R 4.0 (R-Core-Team 2020).

Results

Canopy cover and preserved volcanic ash thickness 6 years after the volcanic eruption

Canopy cover differed significantly between land-use systems (Fig. 2a). The lowest canopy cover was found in CR (12.7%). No significant differences were found in canopy cover between CAF and SAF (an average of 75%). Finally, the highest canopy cover was observed in DF (88.2%). The canopy cover variability under tree-based systems was lower compared to CR.

Preserved volcanic ash thickness across all different sampling points ranged from 2 – 14 cm, with an average of 8.5 cm (Fig. 2b). DF had the highest volcanic ash thickness (9.9 cm) followed by CAF (7 cm), with no significant difference between SAF and CR. Volcanic ash thickness in SAF and CR was 23% thicker than CAF, with an average of 8.6 cm. The volcanic ash thickness variability under CR was higher compared to DF and agroforestry systems.

We found no relationship between canopy cover and preserved volcanic ash thickness six year post volcanic eruption ($R^2 = 0.03$, $p = 0.3$). However, we identified a more consistent pattern and significant relationship between volcanic ash thickness and plot position in each local relief ($R^2 = 0.28$, $p < 0.001$). Plot situated in lower slope position (valley) had 25 and 85% thicker of volcanic ash layer than in the middle and upper part, suggesting that land-used systems

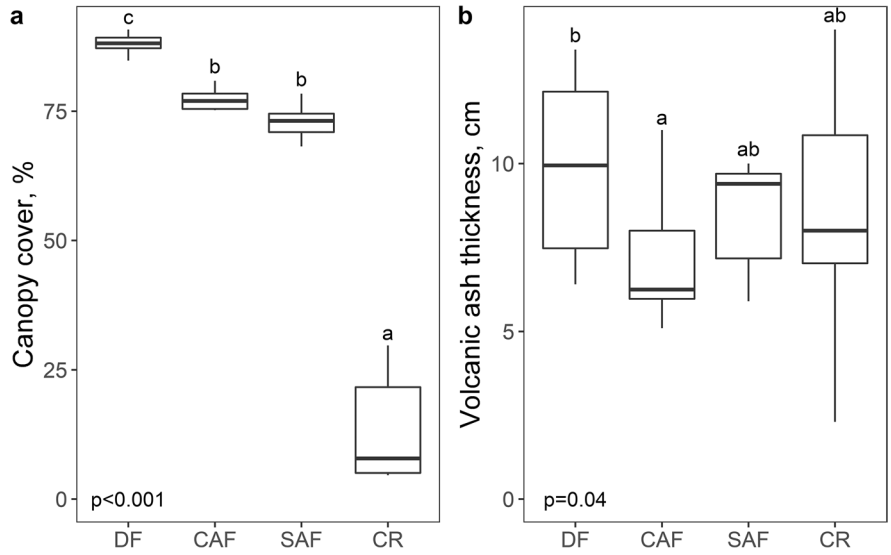


Fig. 2 (**a**) Canopy cover and (**b**) Volcanic ash thickness in various land-use systems (DF = remnant (degraded) forest, CAF = coffee-based complex agroforestry, SAF = coffee-based simple agroforestry, CR = annual crop). Different letters indicate significant differences between land-use systems ($p \leq 0.05$)

and slope position were confounded on volcanic ash preservation.

Litter thickness recovery across land-use systems post volcanic eruption

Litter thickness differed significantly across land-use systems and between observation periods ($p < 0.001$). The highest average of litter thickness was found in DF (1.17 cm), followed by SAF, CAF, and CR (0.88, 0.68, and 0.05 cm, respectively). Overall, litter thickness in 3 YAE (on average 0.38 cm) was noticeably lower than in PRE and 6 YAE (0.75 and 0.82 cm, respectively).

Litter thickness of tree-based land-use systems was increased significantly within 3 to 6 YAE (Fig. 3). Litter thickness in CAF in 6 YAE was higher than PRE condition, indicating complete recovery. Assuming that the original litter layer was entirely covered with tephra deposition, the highest litter accumulation rate during the first three years was in DF (0.22 cm year^{-1}), followed by CAF, SAF, and CR (0.16, 0.12, and 0.007 cm year^{-1}, respectively). The accumulation rate in DF and CAF was reduced to 0.15 and 0.10 cm year^{-1} within 3 to 6 YAE. In contrast, the litter accumulation rate in SAF remained high with 0.13 cm year^{-1}. Based on the 6 YAE datasets, we found that litter thickness increased with

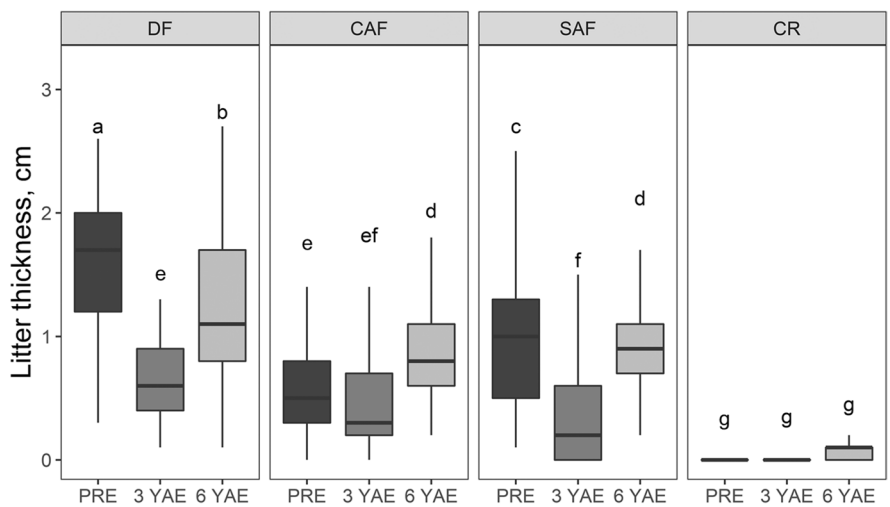


Fig. 3 Litter thickness in various land-use systems (DF = remnant (degraded) forest, CAF = coffee-based complex agroforestry, SAF = coffee-based simple agroforestry, CR = annual crop) and three different periods (PRE = pre eruption, 3 YAE = 3 years after eruption, and 6 YAE = 6 years after eruption). Different letters indicate significant differences between land-use systems and periods ($p \leq 0.05$)

the denser canopy cover ($R^2 = 0.78$, $p < 0.001$). The increase of 10% canopy cover estimated could add 0.25 cm of litter layer.

Soil properties recovery across land-use systems post volcanic eruption

Soil organic carbon (C_{org}) and soil carbon stocks (soil C stocks)

We found that C_{org} and soil C stocks differed significantly across land-use systems ($p < 0.001$). The average C_{org} and soil C stocks were substantially higher in DF (2.15% and 54.36 Mg ha^{-1}), followed by CAF (1.24% and 37.48 Mg ha^{-1}) and SAF (0.97% and 28.1 Mg ha^{-1}), while CR was the lowest (0.7% and 22.05 Mg ha^{-1}). We found no significant difference in average C_{org} and soil C stocks between observation periods (1.26% and 35.5 Mg ha^{-1}). However, C_{org} and soil C stocks of DF and CAF in 6 YAE were marginally higher than in PRE conditions, indicating soil rejuvenation (Table 1).

If we assume that C_{org} of fresh volcanic ash is zero, the C_{org} accumulation rate during the first three years was significantly higher in DF (0.67% year^{-1}), followed by SAF, CAF, and CR (0.34, 0.32, and 0.32% year^{-1}, respectively). C_{org} of DF and CAF continuously increased within 3–6 years post-eruption (0.17 and 0.07% year^{-1}, respectively), conversely to SAF and CR, which were reduced at a rate of 0.01 and 0.13% year^{-1}, respectively.

Mean weight diameter (MWD) and soil porosity

Soil aggregate stability as represented by MWD differed significantly across land-use systems and observation periods ($p < 0.001$). The weakest soil aggregate stability was found at 3 YAE (1.55 mm). There was no significant difference in MWD between PRE and 6 YAE (average 2.67 mm), indicating complete soil aggregate recovery (Table 1). Within land-use systems, the lowest MWD was found in SAF and CR (average 1.8 mm), while DF had almost two times higher MWD than SAF and CR (3.47 mm).

We found no significant difference in soil porosity within observation periods (average of 55%). However, soil porosity differed across land-use systems. The highest average soil porosity was found in DF (61%), followed by CR (56%). The lowest soil porosity was found in CAF and SAF (average 53%). There was no significant difference in soil porosity found between PRE and 6 YAE across land-use systems (Table 1), which may correlate to negligible soil texture changes during observation periods. The composition of volcanic ash deposition (81% sand, 14% silt, and 5% clay) slightly changed the soil texture in the early years after a volcanic eruption. The texture of mixed soil and volcanic ash layer in 3 YAE was sandy loam (54% sand, 34% silt, and 13% clay), while

Table 1 Soil organic carbon (C_{org}), soil carbon stocks (Soil C stocks), mean weight diameter (MWD), and porosity in each land-use system (DF = remnant (degraded) forest; CAF = coffee-based complex agroforestry; SAF = coffee-based simple agroforestry; CR = annual crops; LUS = land-use systems). Each value indicates means ± standard error (SE). Different letter indicate significant differences between land-use systems and periods ($p \leq 0.05$)

LUS	Periods	C_{org}, %	Soil C stocks, Mg ha^{-1}	MWD, mm	Porosity, %
DF	PRE	1.93 ± 0.15^{ab}	50.93 ± 3.84^{ab}	4.65 ± 0.08^{a}	58.57 ± 0.86^{ab}
DF	3 YAE	2.00 ± 0.35^{ab}	45.43 ± 8.48^{ab}	1.59 ± 0.20^{cd}	64.53 ± 0.91^{a}
DF	6 YAE	2.50 ± 0.26^{a}	66.70 ± 5.98^{a}	4.18 ± 0.40^{ab}	58.53 ± 0.96^{ab}
CAF	PRE	1.60 ± 0.35^{abc}	48.60 ± 9.49^{ab}	3.05 ± 0.27^{bc}	51.63 ± 1.20^{cde}
CAF	3 YAE	0.97 ± 0.09^{bc}	28.40 ± 2.25^{bc}	1.59 ± 0.19^{cd}	53.90 ± 2.06^{bcd}
CAF	6 YAE	1.17 ± 0.20^{bc}	35.40 ± 6.70^{bc}	1.73 ± 0.52^{cd}	54.00 ± 0.17^{bcd}
SAF	PRE	0.83 ± 0.12^{c}	27.57 ± 2.99^{bc}	1.76 ± 0.15^{cd}	47.87 ± 2.50^{de}
SAF	3 YAE	1.03 ± 0.19^{bc}	26.90 ± 4.66^{bc}	1.52 ± 0.28^{d}	55.87 ± 1.27^{bc}
SAF	6 YAE	1.00 ± 0.06^{bc}	29.87 ± 1.30^{bc}	2.87 ± 0.13^{bcd}	53.23 ± 0.39^{bcde}
CR	PRE	0.57 ± 0.19^{c}	16.00 ± 5.26^{c}	1.69 ± 0.36^{cd}	59.77 ± 1.13^{ab}
CR	3 YAE	0.97 ± 0.19^{bc}	34.17 ± 6.38^{bc}	1.51 ± 0.30^{d}	47.33 ± 1.37^{e}
CR	6 YAE	0.57 ± 0.07^{c}	15.97 ± 1.82^{c}	1.46 ± 0.28^{d}	59.57 ± 0.57^{ab}

in PRE and 6 YAE were loam (50% sand, 36% silt, and 14% clay).

Soil infiltration recovery across land-use systems post volcanic eruption

Steady-state infiltration rate markedly differed after tephra deposition, from an average of 28.9 cm hour^{-1} in PRE plummeting to 3.7 cm hour^{-1} in 3 YAE (Fig. 4). However, the soil infiltration was quickly recovered to its PRE condition after six years. The fastest average soil infiltration was found in DF (38 cm hour^{-1}), while the lowest was in CR (4 cm hour^{-1}). There was no significant difference between CAF and SAF (average 20.5 cm hour^{-1}).

Relationships between litter thickness, soil properties and infiltration

We expected that the litter thickness has a definite correlation to C_{org}. However, we found an insignificant positive association between C_{org} and litter thickness during the early years after volcanic eruption (Fig. 5). The relationship between litter thickness and C_{org} became substantial with time (Fig. 6), suggesting that a land-use system with a thick litter layer is more likely to have higher C_{org} content.

The soil surface protection from the litter layer contributed to the higher soil infiltration, as shown by the solid and consistent relationships between variables throughout observation periods. Additionally, the differences in vegetation and soil management practices of each land-use system potentially influenced soil infiltration through soil properties modification. Litter thickness and C_{org} were strongly correlated to porosity in the early years after the volcanic eruption. Higher soil porosity indeed had a positive impact on soil infiltration. However, a substantial difference in infiltration rate between 3 and 6 YAE showed that higher soil porosity was insufficient to deliver faster infiltration without better soil aggregate stability. We found a significant correlation between litter thickness, C_{org}, and MWD with soil infiltration in 6 YAE, supporting our previous finding.

Discussion

The relation between canopy cover and volcanic ash thickness

We observed that the average volcanic ash thickness 6 YAE of each LUS was within 7—9.9 cm. However, the initial volcanic ash layer may be thicker than the 'preserved' volcanic ash we measured. Blong et al. (2017) discovered that the average tephra thickness in various vegetation types and slopes was 40% less than its original fallout after two years of tephra redistribution and compaction process. Based on that, we estimated that the initial volcanic ash fallout deposited in our study area was approximately 9.8 – 13.9 cm. These estimates were within the range (10–20 cm)

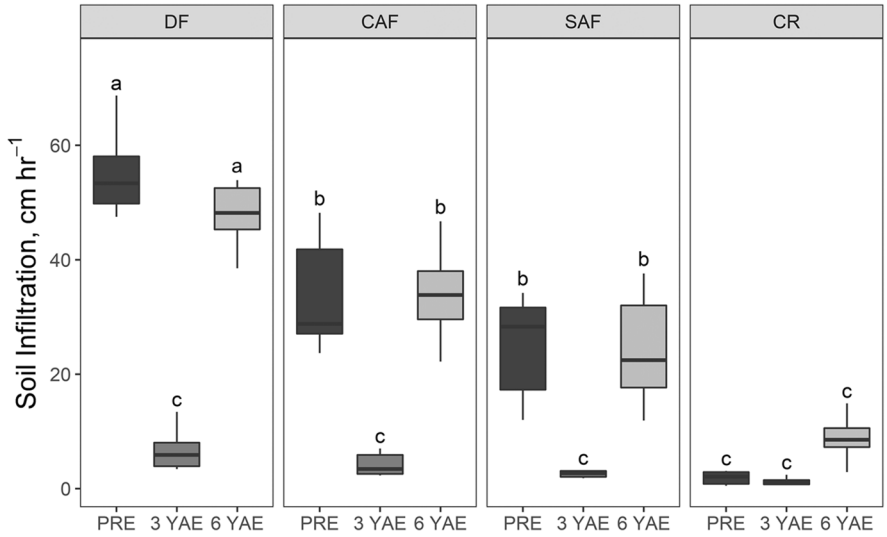


Fig. 4 Soil infiltration in various land-use systems and three different periods (DF = degraded forest, CAF = coffee-based complex agroforestry, SAF = coffee-based simple agroforestry, CR = annual crops; PRE = pre eruption, 3 YAE = 3 years after eruption, and 6 YAE = 6 years after eruption). Different letters indicate significant differences between land-use systems and periods ($p \leq 0.05$)

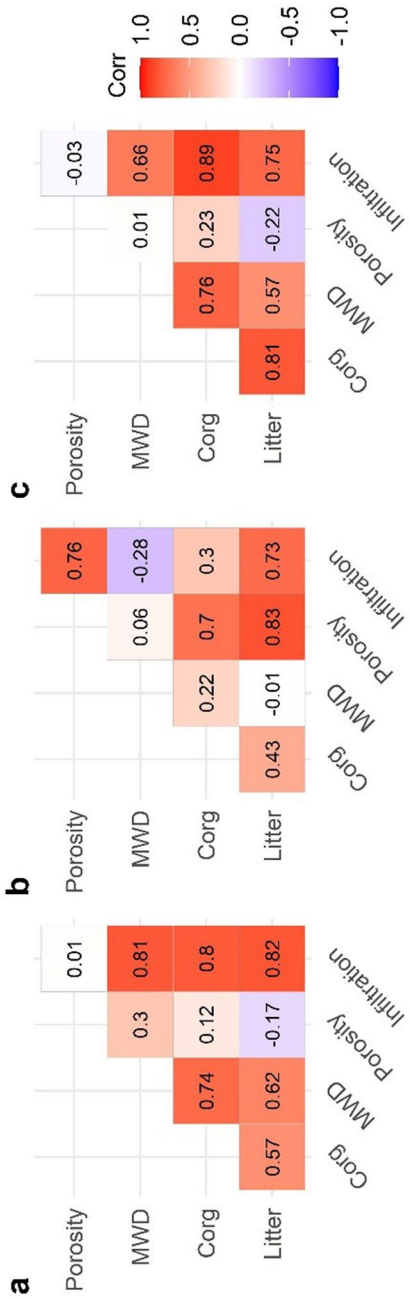


Fig. 5 Coefficient correlation of litter thickness (Litter), soil organic carbon content (C_{org}), mean weight diameter (MWD), soil porosity (Porosity), and soil infiltration (Infiltration) in **(a)** PRE eruption, **(b)** 3 YAE, and **(c)** 6 YAE. YAE = year after the eruption. The colour and number inside the boxes indicate the correlation value

of the initial/original ash fallout measured near the research area in an open field a month after the 2014 Mt. Kelud eruption (Nakada et al. (2016).

We expected that volcanic ash thickness had a positive association with the canopy density. However, volcanic ash thickness correlated more to the plots' slope position in the local relief rather than canopy cover. The lateral mobilisation and stabilisation of volcanic ash by water and air erosion occurred after the volcanic eruption resulting in a downslope thickening of the volcanic ash layer. Additionally, we found that the volcanic ash thickness in monoculture crops had higher variability than in the forests and agroforestry systems (Fig. 2b). Our results agreed with Dugmore et al. (2018), which found that sloping sites with a consistent canopy cover such as forested areas might produce more reliable and uniform stratigraphic records of fallout than the flat sites with varied vegetation. The exposed condition in the open, scatter, and short vegetation resulted in sharp local air and water erosion variation, leading to tephra thickening under the vegetation patches and marked small-scale variability in tephra thickness (Cutler et al. 2016).

Soil properties and function recovery after volcanic ash deposition across land-use systems

Soil recovery is essential in ecosystem succession after significant disturbance from volcanic ash deposition following a volcanic eruption. The recovery starts with the interactions between remaining/surviving organisms and new colonists that could modify the site conditions such as nutrient input and water availability (Antos and Zobel 2005). As an energy source, organic matter availability drives these interactions. For the context of the volcanic soil, the increase of organic matter inputs from organic fertiliser and/or above- and belowground plants biomass, alongside the exceptional capability of volcanic ash to sequester and store a large quantity of carbon, could accelerate the soil organic carbon and soil C stocks accumulation (Fiantis et al. 2016).

However, the lower litter thickness in CR was not reflected in smaller C_{org} content. The correlations between litter thickness (representing aboveground biomass production and decomposition balance) and C_{org} was insignificant, particularly in 3 YAE (Fig. 6). This result indicates that the manure application

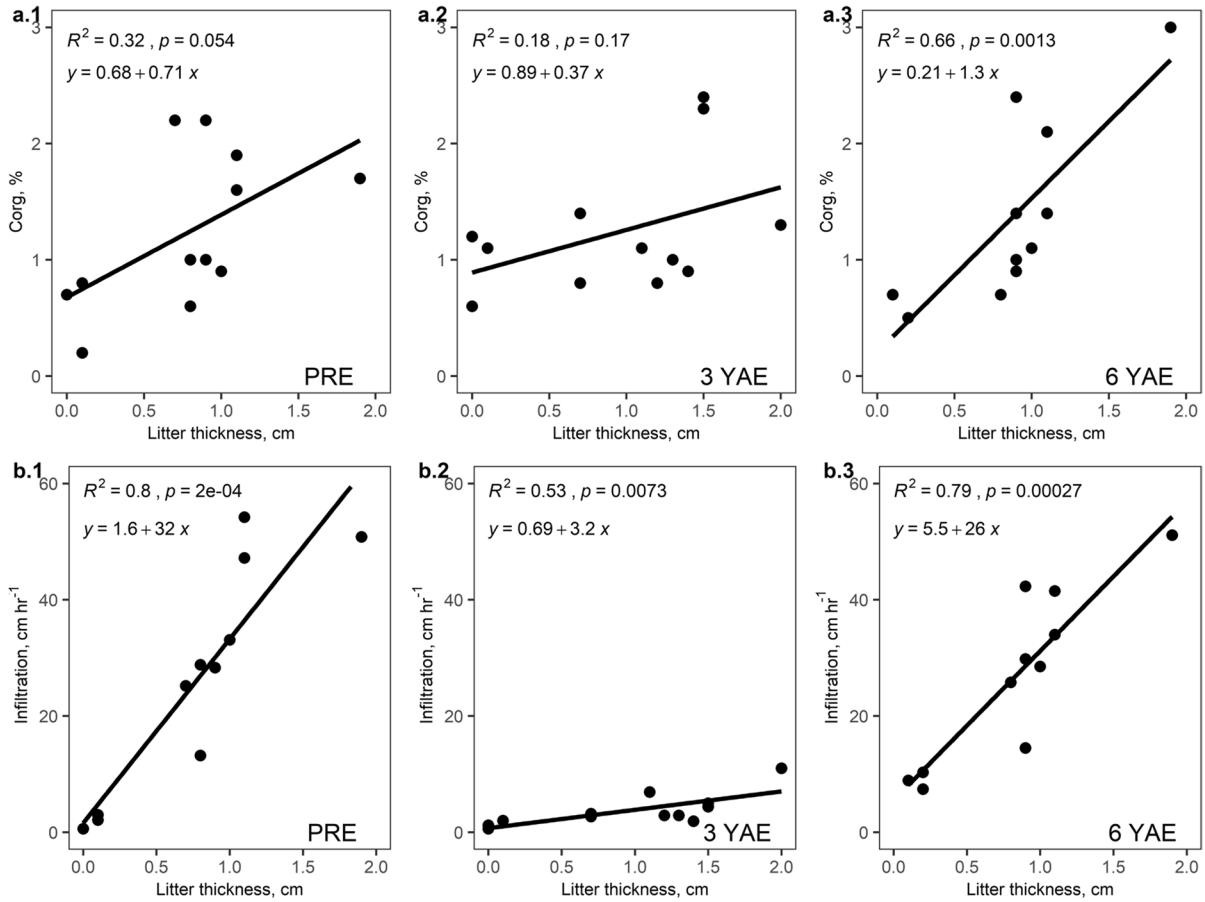


Fig. 6 Relationships between litter thickness and **(a)** C_{org} content, and **(b)** soil infiltration in three different periods of (**1**) PRE eruption, (**2**) 3 YAE, and (**3**) 6 YAE. YAE = year after the eruption

(5.4 Mg ha^{-1} year^{-1}) in CR during the early year post-eruption could accumulate C_{org} comparable to agroforestry systems with its thick litter layer. However, CR roughly needs two times higher organic matter input to maintain its C_{org} at the level of agroforestry systems in the long term. A study by Ferreiro et al. (2020) in Argentina confirmed that the application of organic matter (compost) could promote short-term rehabilitation of open bare-soil affected by tephra deposition.

Three years after the eruption, DF had a higher C_{org} accumulation rate (average of 0.68% year^{-1}) than the other LUS (0.32 – 0.35% year^{-1}). These early years C_{org} accumulation rate of volcanic ash was similar to the study conducted by Fiantis et al. (2019) in Mt. Talang with a sequestration rate of 0.2 – 0.5% year^{-1} but relatively lower than Mt. Sinabung (0.53 – 1.4% year^{-1}). However, it was relatively high compared to those found in temperate regions (Ferreiro et al. 2018; Halvorson and Smith 2009; Halvorson et al. 2005). Nevertheless, it appears that the high soil carbon sequestration rate in soil material derived from volcanic ash is not reflected in the existing IPCC national accounting standard that is based on the 0–30 soil layer, without acknowledging the addition of 'new' soil. Adjustments in the accounting systems may be needed (Hairiah et al. 2020; Minasny et al. 2021) before these volcanic soils are recognized for exceeding the targets of the '4 per mille Soil for Food Security and Climate' initiative (Minasny et al. 2017).

The most dramatic change following the volcanic eruption was the substantial shift in infiltration rate (Fig. 4). The average infiltration rate of 29 cm hour^{-1} in PRE condition dropped to only 3.7 cm hour^{-1}

within three years after volcanic ash deposition. The latter can be exceeded during rainstorms, leading to overland flow. Our finding agrees with earlier studies that showed a double-digit soil infiltration change after tephra deposition (Arnalds 2013; Major and Yamakoshi 2005; Pierson and Major 2014). The volcanic ash deposition on top of the soil surface creates encrusted surface strata with low hydraulic conductivity and infiltration (Anda et al. 2016; Pierson and Major 2014; Tarasenko et al. 2019). However, we found no substantial difference in soil porosity between PRE and 6 YAE. This result indicates that beyond total porosity as such, the distribution and orientation of soil particles, the diameter, tortuosity, and connectivity of macropores can influence soil infiltration. Faster soil infiltration has been linked to a higher proportion of surface-connected soil macropores and more stable soil aggregate in volcanic (Müller et al. 2018; Tejedor et al. 2013) and non-volcanic soils (Bryk and Kołodziej 2021; Saputra et al. 2020). These two determining factors were the manifestation of higher organic matter availability combined with highly active soil ecosystem engineers through the bioturbation process. On the other hand, the rapid loss and recovery of infiltration capacity on volcanic soils may have additional causes. The lower soil infiltration may be related to the emergence of soil water repellency caused by the combination of the hydrophobic characteristic of volcanic ash (Berenstecher et al. 2017) and hydrophobic substances derived from soil organic matter decomposition (Jimenez-Morillo et al. 2017; Kawamoto et al. 2007; Neris et al. 2013; Poulenard et al. 2004).

Nevertheless, the soil regained its infiltration rate equal to the PRE condition after six years, except for CR. At this point, the predominant surface hydrological functions in this watershed had returned to pre-eruption states under normal precipitation conditions. Our result agrees with the study performed by Major and Yamakoshi (2005), which showed the rapid change in infiltration capacity after tephra deposition. Tree-based systems could provide better soil infiltration rate compared to monoculture crops during medium-long timeframes because: (1) the systems have a sufficient supply of soil organic matter used by soil ecosystem engineers to create a better soil macropore and aggregate stability; (2) dense canopy cover could regulate microclimate that favourable for more active soil organisms during the bioturbation process; (3) together with closed canopy cover, thick litter layer produces by trees could provide direct soil surface protection, and guarantee surface-connected macroporosity for a faster infiltration and lower soil erosion, thus improves water balance on the systems (Chen et al. 2017; Hairiah et al. 2006; Saputra et al. 2020; van Noordwijk et al. 2019).

Overall, our study provides new insights into the short-medium term impact and recovery of soil properties and functions after volcanic ash deposition across different LUS. The severe but temporary shifts of some soil properties, such as aggregate stability and soil infiltration, were unavoidable in natural and agricultural systems during the early years after volcanic ash deposition. The recovery phase of a particular LUS depends on its plants and soil management. However, not all soil attributes changes can be described as recovery. Some attributes might diverge farther from the pre-disturbance condition due to the continuing change of the system internally (soil and plant management) as well as climate change. As stated by Antos and Zobel (2005), "the fundamental difficulty assessing post-disturbance succession and rates or convergence on the previous condition is that even old forests are constantly changing". Nevertheless, a comprehensive study using a proper simulation model that can minimise those uncertainties might improve our understanding of the complete cycle of soil functions recovery process after the volcanic eruption.

Conclusions

We found that preserved ash thickness was related to the plot position on the local relief rather than by canopy cover. The volcanic ash mobilization and stabilization process resulted in a downslope thickening of the ash layer. The relatively closed canopy cover of tree-based systems generated more homogenous volcanic ash layers than the exposed and scattered short-vegetation in CR. Relatively thick volcanic ash deposition onto the soil surface affected soil physical properties positively and negatively. Volcanic ash deposition homogenized soil properties and function across different LUS during the short term. Litter thickness, MWD, and soil infiltration changed rapidly after volcanic ash deposition but quickly recovered. In contrast, soil C_{org}, soil C stocks, and porosity were unchanged. Different land-use management results in

different recovery trajectories of soil physical properties and function over the medium-long term.

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Author contributions All authors contributed to the study conception, plan, and design. DDS and RRS conducted the material preparation, data collection and fieldwork. DDS and RRS compiled and analysed the data. DDS and MvN wrote the first draft of the manuscript and all authors commented on previous versions of the manuscript. All authors have read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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